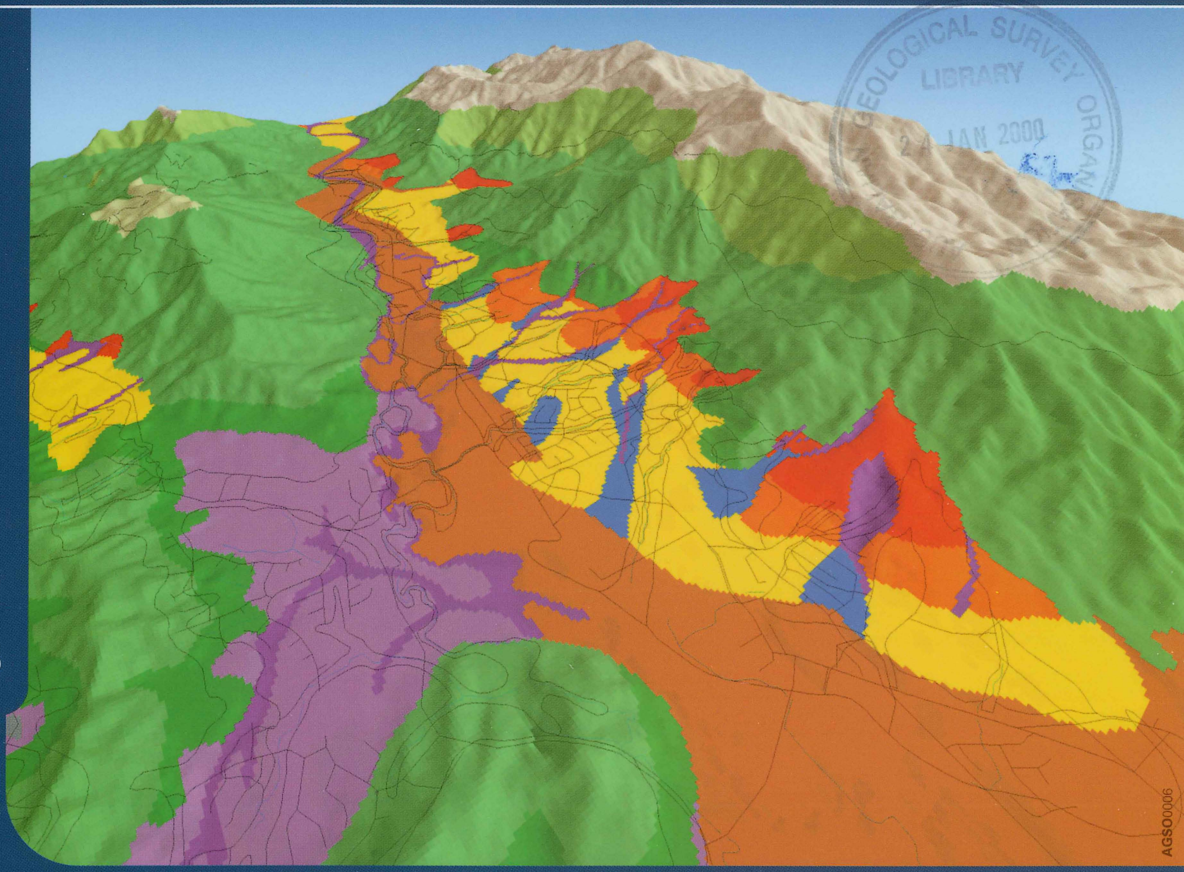
Quantitative Landslide Risk Assessment of Cairns



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Cities Project

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SUMMARY

This is a report describing a quantitative landslide risk assessment carried out in the Cairns area as part of the AGSO *Cities Project.* The study objective is to provide information on landslide types, community vulnerability and risks to the Cairns City Council for planning and emergency management purposes.

Using geological and geomorphological observations and historical information, a regional map of landslide hazards in the Cairns area has been produced. This map was entered into a geographic information system (GIS) containing comprehensive information on buildings, roads and demography.

Two main landslide slope processes have been identified. The first group are the landslides (mainly rock falls, rock slides, debris slides, and small debris flows) that occur on slopes developed in weathered bedrock and thin colluvial cover. The second group of landslides, which had not been identified as a threat previously, are occasional large debris flows (containing boulders up to several metres in diameter) which extend from the major gully systems on to the plains and form fans at the base of the slopes. Small landslides (wall collapses) in the walls of trenches or cuttings in the plains were not included in this study.

The landslide hazard was assessed quantitatively using the following methodology.

The magnitude of a landslide was defined as the logarithm of its volume in cubic metres. Using a detailed catalogue of events based on field observations in Cairns and extensive historical research, magnitude-recurrence relations were derived for the two groups of landslides.

The extent to which future debris flows might extend from gullies has been estimated using an approach based on "shadow angles" that geometrically define run-out distances. Thus areas that have been or could be impacted by debris flows have been defined.

GIS polygons have been used to delineate and characterise the areas that could be affected by landslides. Three main categories were chosen:

- the escarpment;
- areas which could be affected by the proximal portions of debris flows; and,
- areas which could be affected by the distal portions of debris flows.

The proximal portion is that part of the debris flow closest to the source of the landslide. It has a lumpy or convex surface and contains large boulders up to several metres in length. The distal portion of a debris flow is the more gently sloping and contains the finer grained sediments that are deposited further from the landslide source.

In the following text, the average recurrence intervals (ARI) and hazard and risk probabilities per annum have been rounded to one significant figure. This is because of the large uncertainties in the estimates – the error bars on the ARI graphs are up to two orders of magnitude.

For each polygon, information on the ARI for various landslide magnitudes has been used to estimate the landslide hazard (probability, *H*, per annum of a point being impacted by a

landslide) for the Cairns area. For points on hill slopes, the hazard occurrence probability is estimated to be 0.02% (an ARI of 6000 years), assuming that the slope is developed. Thus, for undeveloped parts of the escarpment, this figure predicts what the hazard would be *if* the slope were to be developed *without adequate mitigation measures being taken*. The hazard would be expected to be considerably less on slopes developed with appropriate engineering practice based on detailed geotechnical consultation. It would also probably be less on undisturbed slopes. The hazard probability in areas which may be impacted by the proximal parts of debris flows is calculated to be 0.01% (0.00012, an ARI of 8000 years), and for the distal parts of debris flows, 0.01% (0.00011, an ARI of 9000 years).

The GIS polygons have then been interrogated to assess the nature and number of elements at risk (E). The vulnerabilities (V) of people, buildings and roads to destruction by landslides and debris flows were assessed. The vulnerability was taken to be the probability of destruction given that the person, building or road was hit by a landslide.

Specific annual risk of destruction is the probability per annum of a person, building or section of road at a given point in the Cairns area being destroyed by a landslide. The specific risks to individual people, buildings and roads in susceptible parts of Cairns, if the areas were to be developed, have been calculated from the equation

$$specific\ risk = H \times V$$

and mapped using the GIS.

A risk map depicting the estimated annual probability of a total road blockage somewhere in any 10 km length of road parallel to the escarpment was also prepared. For the hill slopes, the estimated annual probability is 60% (an ARI of one to two years). For roads in potential proximal debris flow runout regions it is 1% (an ARI of 100 years), and in potential distal debris flow runout regions it is 0.4% (an ARI of 200 years).

The specific annual risk of destruction of individuals, buildings and roads, and of road blockage is tabulated below. The possible range in values, attributed to uncertainties in the recurrence relations, is given in brackets.

Unit	**Specific annual risk of death – resident people**	**Specific annual risk of building destruction**	**Specific annual risk of road destruction**	**Specific annual risk of road blockage**
Hill slopes	0.0008% 1 in 100 000+ *(1 in 5 million to 1 in 40 000)*	0.004% 1 in 20 000 *(1 in 1 million to 1 in 8000)*	0.005% 1 in 20 000 *(1 in 1 million to 1 in 8000)*	0.02% 1 in 6000 *(1 in 300 000 to 1 in 2000)*
Units susceptible to proximal debris flow	0.01% 1 in 9000 *(1 in 50 000 to 1 in 2000)*	0.01% 1 in 8000 *(1 in 50 000 to 1 in 1000)*	0.01% 1 in 8000 *(1 in 50 000 to 1 in 1000)*	0.01% 1 in 10 000+ *(1 in 60 000 to 1 in 2000)*
Units susceptible to distal debris flow	0.0005% 1 in 200 000 *(1 in 1 million to 1 in 30 000)*	0.001% 1 in 90 000 *(1 in 500 000 to 1 in 20 000)*	0.003% 1 in 30 000 *(1 in 200 000 to 1 in 5000)*	0.007% 1 in 10 000+ *(1 in 60 000 to 1 in 2000)*

Total risk is the number of elements at risk expected to be destroyed by a landslide in a given GIS polygon in a given period of time. Maps which quantitatively depict the total risks per km^2 per 100 years for residential people and buildings in each GIS polygon in the currently developed parts of Cairns, were constructed from the data for each polygon. These were based on the equation

$$total\ risk = H \times E \times V$$

where E is the number of houses and blocks of flats, or people living in houses and flats, in a polygon. The greatest total risk for buildings (houses and blocks of flats) is on the hill slopes, where it is estimated that a total of 13 buildings throughout the map area could be destroyed in 100 years, *if no mitigation measures had been taken*. The highest total risk for people living in houses and flats is in the proximal parts of debris flows. It is estimated that a total of 16 people in the map area could be killed over a 100 year period as a result.

Because the Captain Cook Highway, Kuranda Range Road and Cairns-Kuranda Railway, which provide access to Cairns from the north and the Tableland, each pass through country with steep slopes, they may be blocked by landslides in the event of intense precipitation such as that associated with tropical cyclones. Outside the study area, the Bruce Highway and particularly the Gillies Highway (which links Gordonvale to the Atherton Tableland), may also be blocked by landslide. This makes the Cairns community particularly vulnerable to isolation.

Flash flooding in Freshwater Creek, or debris flows, have the potential to disrupt the Cairns water supply by blocking the intake or destroying sections of the pipeline.

The limitations of this reconnaissance study are:

- the paucity of the data from which the landslide magnitude-recurrence relations were derived. As the error bars for the data points are, in some cases, more than two orders of magnitude, errors in the risk estimates may be large;
- the regional nature of this study. Mapping was at a reconnaissance level, only;
- the assumption of a uniform process rate across, and from top to bottom of, the entire escarpment profile, irrespective of local geomorphology, rock type, soil cover or position on the escarpment;
- the assumption that the shadow angles are uniform for all debris flows in the area;
- the *lower* limit for landslide volume in the risk assessment calculations was 32 m^3;
- the assumption that vulnerability is independent of landslide magnitude;
- the assumption that debris flow runout is unaffected by the presence of large obstacles;
- the assumption that landslide intensity is uniform across a landslide;
- lack of discrimination between the effects of shorter duration, higher intensity rainfall events, of antecedent rainfall, and of longer duration, lower intensity rainfall events. The data tend to be skewed towards observations after tropical cyclones, which tend to be shorter duration, higher intensity rainfall events; and
- rotational or translational slides in debris flow fans, and landslides in walls of trenches and cuttings have not been considered in the risk assessment.

Finally, the reconnaissance nature of the field mapping must be emphasised. Polygon boundaries are approximate only and some details on the landslide data map may change with further and more detailed field work. For detailed site-specific assessments, our broad findings should be checked by geotechnical specialists.

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1 INTRODUCTION

As part of the *Cities Project*, a preliminary landslide risk assessment was performed in the Cairns area, in north Queensland. The work was carried out by the Australian Geological Survey Organisation, assisted by Dr Fred Baynes, a consulting engineering geologist. The bulk of the field work and a preliminary landslide risk assessment were undertaken during the period February to July 1997. Analysis of results, follow-up field work, and report writing continued intermittently until September 1999.

2 AIM AND SCOPE

The aim of this landslide assessment is to map, document and understand the landslide hazard, assess the vulnerability of the Cairns community with regard to the threat of landslide, and to quantify the risk to life and property.

The present-day boundaries of Cairns City were established in 1995 following the amalgamation of the former local governments of Mulgrave Shire and Cairns City. The area covered by this study extends from Ellis Beach in the north to Gordonvale in the south. It also includes the Yarrabah Aboriginal Community to the east of Cairns. The study area is indicated in Figure 1.

Due to the limited financial and human resources available for the study, and the size of the study area, the assessments can only be regarded as an initial regional overview of landslide risks in the Cairns area.

It is intended that the landslide risk assessment will provide information to Cairns City Council and, in particular, the emergency management group and planners within the Council.

This report also documents the development of a GIS based regional landslide risk assessment methodology, and the practical application of that methodology in the Cairns area. As this methodology is still being developed the report should only be considered as documenting an interim stage in the research.

3 BACKGROUND

3.1 Nature of the *Cities Project*

The Cairns landslide hazard and risk assessment is part of AGSO's *Cities Project*.

The *Cities Project* undertakes research towards the mitigation of the risks posed by a range of geohazards to Australian urban communities. The ultimate objective is to improve the safety of communities, and consequently make them more sustainable and prosperous.

The *Cities Project* is at present in its developmental phase. Techniques, methodologies and standards are being developed and tested in "real world" pilot studies. *Community Risk in Cairns* is the first of a series of multi-hazard risk assessment case studies by the AGSO *Cities Project*. It considers earthquake, landslide, flood and cyclone impact. A report (Granger *et al*, 1999) detailing the hazard history of Cairns, the risk assessment methodology and results was released on CD-ROM with a hard copy overview in April 1999.

Risk is the outcome of the interaction between a hazard phenomenon and the vulnerable elements at risk (the people, buildings and infrastructure) within the community. *Risk-GIS*, as it has been christened in the *Cities Project*, uses the power of GIS as a decision support tool in risk management, following the process outlined in AS/NZ Standard 4360: 1999 Risk Management (Standards Australia, 1999).

The fieldwork for the landslide pilot study was conducted for 16 days in March, four in April and two in June 1997. The first draft of the landslide risk assessment report was completed in July 1997. A field review by Alan Moon of Golder Associates, in the company of Fred Baynes and Marion Leiba, was carried out for five days in late July - early August 1997. A revised draft was completed in July 1998, taking most of the reviewer's comments into account. Marion Leiba did a three day field assessment of landslides triggered by Cyclone *Rona* in February 1999, and a three day examination in April 1999 of the effects on slope stability of the prolonged heavy rain in February-March 1999, subsequent to *Rona*. The final version of the report was prepared in September 1999.

3.2 Regional Geology and Geomorphology

The regional geology and geomorphology is sourced from the Cairns Region 1:100 000 Geological Map and Commentary (Queensland Department of Mines, 1988).

Bedrock in the Cairns region consists of a more than 200 million year old sequence of folded and cleaved metamorphosed sediments, and granite bodies. The prominent escarpments behind Cairns are believed to have been formed from a modified land surface, more than 65 million years old, which was formerly a continental highland; the granite bodies probably formed the highest points on this land surface because of their resistance to erosion. Around 60 million years ago, the eastern part of the continental highland was rifted, leaving a steep eastern slope. This slope has been retreating since then to reach a position, about a million years ago, close to that of the present. Erosion has occurred most rapidly in the metamorphosed sediments, leaving the granite as isolated hills and ranges. Whether or not there has been further uplift or faulting since the rifting around 60 million years ago is not known. There is no direct evidence that the Trinity Inlet – Mulgrave River corridor is a former rift valley, but this seems possible given the physiography and geological associations.

The modern Cairns area consists of the plateau on which Kuranda is built, the rocks and landslide deposits of the escarpment, and the largely alluvial deposits of Trinity Inlet, the Barron River mouth, the Freshwater Valley, and the coastal plain.

The escarpment continues to be worn back by erosion and landslides. On the coastal plain, near the foot of the escarpment, a number of debris flow fans and deposits are found.

A simplified geological map of the area is presented as Figure 2 and the geological history of the area is summarised in Table 1.

3.3 Climate and Vegetation

The area has a wet tropical climate, with distinct wet and dry seasons. The heaviest rain occurs during the summer months. Rainfall is over 2000 mm per annum in the coastal corridor, influenced by the proximity of the 700 m-high escarpment to the west; it increases to about 7000 mm on the summit of the range behind the escarpment.

The following information in this section is from Granger *et al*, 1999.

"Extreme rainfall events are associated with tropical cyclones. Cairns comes under the influence of tropical cyclones on average at least once every two years; though 'direct hits' by severe tropical cyclones are not common.

Temperatures rarely exceed 35.0°C or go below 10.0°C for extended periods."

Statistics on rainfall intensity and climate are summarised in Tables 2(a) and (b).

"The natural vegetation of the area is a species-rich tropical rainforest. Extensive areas of this type still exist along the ranges and are now incorporated, under World Heritage listing, into the Wet Tropics Management Area. Rainforest grades to various forms of eucalypt-dominated forest or woodland and grassland in areas exposed to frequent burning, especially on the hill slopes. Most of the valley and coastal plain areas not occupied by urban development are under sugar cane cultivation or are covered by mangrove communities."

3.4 Nature of Landslides

A landslide is the movement of a mass of rock, debris or earth down a slope. Whilst the causes of slope movement can be quite complex, all landslides have two things in common - they are the result of failure of part of the soil and rock materials that make up the hill slope and they are driven by gravity. They can vary in size from a single boulder in a rock fall or topple to tens of millions of cubic metres of material in a debris avalanche. Landslides can be caused in a number of ways. These include saturation of slope material from rainfall or seepage; vibrations caused by earthquakes; undercutting of cliffs by waves; or by human activity.

Certainly the most common trigger for landslides is an episode of intense rainfall. The rainfall threshold values for slope failure in various parts of the world are in the range 8 - 20 mm over one hour, or 50 - 120 mm over a day (John Braybrooke, written communication, 1998), depending on geology and slope conditions. In Cairns, rainfall intensities of such magnitude have an average recurrence interval (ARI) of considerably less than one year, and landslides are not rare events.

Debris flows are a type of landslide triggered by the action of torrential rain on loose material (rocks and finer material) on a mountain side or escarpment. The boulders and finer material, mixed with water, flow down the slope as a torrent. The boulders and some of the finer material is deposited near the base of the slope, while the remainder of the finer material travels further as a flash flood. Debris flows can be highly destructive.

3.5 Seismicity

The seismicity and earthquake hazard of the Cairns area are relevant because strong earthquake shaking can trigger landslides (Wieczorek, 1996).

Four earthquakes in northern Queensland are recorded as having been felt in Cairns, but it is not known whether any of them triggered landslides..

On 18 December 1913, a Richter magnitude 5.7 earthquake about 370 km southeast of Cairns was felt there.

The largest in the Cairns region had a Richter magnitude of 4.4 and was strongly felt in Cairns (Everingham *et al,* 1982). Its epicentre was offshore, about 50 km NNW of Cairns, and it happened in December 1958.

The earthquake of February 1896 was the closest to Cairns, the epicentre being 15 km SW of the city (Rynn *et al,* 1987). It had a Richter magnitude of 4.3 and caused cracks in Nos. 3, 4, 9, 10, and 15 tunnels and two concrete culverts on the Cairns – Kuranda railway (Queensland Railways Commissioner, 1896).

The fourth earthquake happened about 40 km south of Cairns in June 1950 (Everingham *et al,* 1982). It had a Richter magnitude of 4.0 and was weakly felt by some people in Cairns.

The earthquake shaking with a 10% probability of being equalled or exceeded in a 50 year period in Cairns (Standards Australia, 1993) may be sufficient to dislodge loose material from existing slips, talus slopes, or shingle slides (Eiby, 1966). Earthquake risk in Cairns is discussed in Granger *et al*, 1999.

3.6 Development

Because Trinity Inlet (Figure 1) was known as an occasional campsite to beche-de-mer fishermen, and had been seen by prospectors, it was chosen as the Hodgkinson Goldfield's first port. A track from the goldfields was blazed to the coast in September 1876, and Cairns was established in October 1876. The population of the new settlement was 400 (Kerr, 1984).

The cutting of red cedar was an important industry. The town grew in the 1880s with the establishment of the sugar industry, and indentured labour was recruited (Johnston, 1984).

After the tin mining town of Herberton was isolated for several months because of a prolonged wet season in 1882, the residents began demanding a railway to the coast. Construction of the Cairns railway commenced in 1886, and was completed as far as Myola in 1891. The topography and landslides during the wet seasons had made construction difficult. The railway reached its original destination, Herberton, in 1910 (Broughton & Stephens, 1984).

The following is from Granger *et al*, 1999.

"Recently, residential development in Cairns has spread to the northern beaches, the low hills and foot slopes of the Whitfield Range, and into the Mulgrave River valley towards Gordonvale. The population of Cairns has grown from 71,500 in 1983, to 128 000 at the 1996 census of whom almost 10 000 were overseas visitors."

"The city is the transport, logistic and administrative centre for an increasingly large hinterland which includes northern Queensland, Torres Strait, and significant mining operations in Papua New Guinea and the Indonesian Province of Irian Jaya. Cairns is now a major tourist destination, and the centre for a significant proportion of Australia's sugar industry and fishing operations in the northern Great Barrier Reef."

3.7 Previous Landslide Risk Studies

A slope stability zoning study of the Cairns area was prepared by G W Hoffman of the Geological Survey of Queensland in 1984 (Hoffman, 1984). Other landslide studies carried out before 1984, including those by Godfrey (1975) and the Co-ordinator General's Department (1978), are summarised by Hoffman (*ibid*).

Hoffman delineated five stability zones and related known landslide occurrences to topographic and geological conditions. The basis of the zoning scheme was as follows:

- Susceptibility to instability can be related to slope angle, with distinctions in the risk of instability at slope angles above one in five (11°) and again above one in three (18°).

- For slopes with the same angle, a distinction in the susceptibility to instability may be made between slopes underlain by granitic rocks, which are less stable, and slopes underlain by metamorphic rocks, which are more stable.

- Because one of the main modes of slope failure is debris flow, the stability zoning should distinguish between convex slopes forming ridge tops, and concave slopes between ridges, where debris flows may accumulate. The concavities between ridges are thus more hazardous.

A land instability assessment of the Cairns area has been carried out by Natural Resource Assessments Pty Ltd (1997). That study is based in part on advice provided by Golder Associates as to the geotechnical controls on instability. It is a GIS based assessment incorporating ranked information based on the following considerations:

- Slope failures have been identified on slopes greater than about 20° where underlain by colluvium.

- The incidence of slope failure is more common in weathered granites than in weathered metamorphic rocks, and aplite dykes may act as groundwater conduits, and thus be associated with instability.

- Shallow slips in weathered metamorphic rocks are thought to be associated with relict joint plains. Instability within these materials generally can be attributed to man made factors, *i.e.* development.

- Previous studies have proposed relationships between slope stability and slope angle or gradient.

- Instability tends to be associated with thicker colluvium, loss of vegetation and previous instability.

However when this study was carried out only limited data delineating areas with attributes relating to these criteria were available in digital format, and accordingly the instability assessment was based on the following criteria:

- geology;
- slope gradient; and
- vegetation cover.

Natural Resource Assessments' decision matrix categorising the potential for land instability is reproduced as Table 3.

4 QUANTITATIVE LANDSLIDE RISK ASSESSMENT METHODOLOGY

4.1 Theoretical Framework

Quantitative landslide risk assessment is a relatively new approach to dealing with landslide zoning or regional stability studies. A workshop on the subject, arranged under the auspices of the International Union of Geological Sciences Working Group on Landslide, involved practitioners from throughout the world and was reported in some detail (Cruden & Fell, editors, 1997).

In its simplest form, quantitative landslide risk assessment involves the following specific steps:

- Assessment of the hazard: the probability of any type of landslide hazard occurring in a defined area within a given period of time (generally one year). This is expressed as a quantitative probability, H. For example, in this report, if the probability of impact of a landslide at a given point in the study area in a year is considered to be one in ten, then H = 0.1.

- Assessment of the vulnerability of life or property to the effects of the landslide. This is expressed as the potential degree of loss of a given element or set of elements within the area affected by the landslide. It is expressed as quantity, V, on a scale of zero (no damage) to one (complete loss). In this report, we have considered only vulnerability to destruction. For example, if it is judged that a particular instance of landsliding has a 50% chance of destroying a property impacted by it, then V=0.5. If it is judged that a particular instance of landsliding will have a one in ten chance of causing a fatality in a building impacted by it, then V=0.1.

- Assessment of the elements at risk, E, which means the population, properties, economic activities, etc in the area potentially affected by the landslides.

- Assessment of the total risk R_t for the various events, which is the expected number of lives lost or injured, damage to property or loss of economic activity or environment. In this report, we have considered the projected number of people killed or buildings destroyed by landslides. It is the product of hazard (H), vulnerability (V), and number of elements at risk (E) in the area under consideration:

$$R_t = H \times V \times E$$

- Assessment of the specific risk R_s for various events, which is the probability that an individual life will be lost or an individual property would be damaged. It is the product of hazard (H) and vulnerability (V) in the area under consideration. In this report, we have taken specific risk to be the probability, at any given point in the study area, that an element at risk may be destroyed by a landslide:

$$R_s = H \times V$$

- Some comparison of the assessed risk with accepted norms to allow the acceptability of the risk to be assessed for the particular circumstances.

The probability (H) of a landslide occurring is a function of the process rate, *i.e.* the rate at which landslides typically develop on the slopes of the area under consideration. The landslide process rate may be conveniently described as a magnitude-recurrence interval relationship in a similar manner to other natural processes such as flood or earthquake. A generic approach may be applied:

- develop a catalogue of events;
- classify events as to their magnitude (M). This can be, for instance, volume, size or kinetic energy with respect to reference conditions;
- process the catalogue to develop magnitude-average recurrence interval relationships for a given area. If a number of events (n) of a given magnitude or greater occur over a period of record (T) then the average recurrence interval (ARI) = T/n; and
- plot M vs ARI or M vs N, where N = number of events per unit time.

ARI = 1/N, where N is the number of events per unit time (e.g. one year) equalling or exceeding a certain size. The data are generally presented on a log/log plot and tend to plot as a straight line (e.g. Baynes, 1995). This plot is of the form of a magnitude/exceedance number plot. The plot expresses the process rate within a given area. Note that there is a variety of plotting methods used and that the choice of method depends upon factors ranging from discipline convention to statistical rigor.

4.2 Study Approach

The approach used in this study involved the following steps:

- mapping, description and interpretation of the geology and geomorphology of the study area in as much local detail as possible, whilst ensuring uniform general coverage of the area. This required consideration of existing reports and publications, interpretation of aerial photographs, discussion with Cairns City Council, local consultants and the Cairns Historical Society, and, most importantly, ground inspection of areas, readily accessible from public land, where it was suspected that landslides of various forms may have occurred;

- definition of the slope processes, especially the landslide types, and their mode of occurrence;

- collection of information on process rates, from which landslide hazard may be assessed. This information essentially relates to how often landslides occur in the historical and geologic record, where they occur, and what appears to trigger landslide events;

- entry of the landslide location data and slope process interpretation into a GIS;

- use of shadow angles and a digital elevation model in the GIS to define areas which may be susceptible to debris flow runout (discussed further in Section 7.1);

- identification of GIS landslide hazard polygons;

- derivation of magnitude-recurrence relations for the landslide slope processes;

- calculation of landslide hazard for the various polygons;

- assessment of the vulnerability of the elements at risk (people, buildings, and roads) to destruction by the various landslide hazards;

- development of GIS maps depicting specific risk of destruction for people, buildings, and roads, and of road blockage, assuming all landslide hazard polygons are developed (for subdivision, e.g. have a network of roads). These maps are useful as a planning tool; and

- development of GIS total risk of destruction maps for resident people, and buildings (houses and blocks of flats) for the developed parts of the landslide hazard polygons. Information on the elements at risk in each landslide hazard polygon was obtained by interrogating the GIS.

This approach is presented schematically in Figure 3. Peer review, reasonableness checks, and consideration of the acceptability of risk estimates, were also used as an essential part of the process, but for simplicity's sake were not included in Figure 3. In this report, the method used for calculating hazard, specific risk, and total risk from a magnitude recurrence relation graph is illustrated in Figure 4, and the methodology is described in detail in Chapter 7.

4.3 Advantages of this Approach

This approach to landslide risk assessment was adopted for the following reasons:

- It is based on an understanding of all the available observational data relating to geology and geomorphology, slope processes and the complex factors that control slope process rates.

- It provides a rigorous, transparent, robust assessment methodology.

- Because it is quantitative, it is more effectively communicated, and more effectively supports the development of management strategies to respond to, and to mitigate against the landslide risks, in proportion to the absolute level of risk.

- Because it is quantitative, it allows comparison with other risks affecting the community. For example, the risks associated with, say, flood can be compared with the risks associated with landslide, and limited resources allocated in proportion to the level of each risk.

This methodology differs from previous Cairns landslide studies in a number of ways.

- Whilst previous hazard assessments may have incorporated an appreciation of probability, vulnerability and the nature of the elements at risk, they did not deal with these considerations specifically. Such non-quantitative hazard assessments are the type of "landslide risk study" that are most commonly carried out (Crozier, 1992). However such studies have their limitations, because the lack of a rigorous quantitative risk assessment framework tends to result in an incomplete picture of the risks, and the resulting qualitative assessment is difficult to communicate effectively. For example, what exactly is meant in the Natural Resource Assessments Pty Ltd (1997) study by a "moderate potential for instability", and how does this differ from a "low potential" as opposed to a "high potential" and what threat do each of these levels of hazard represent to the community?

- Previous studies were based on the concept that landslide risk necessarily increases with slope angle, a concept that can sometimes be misleading. Slope angle usually reflects the age and the strength of the materials underlying the slope but not necessarily the "stability". It is often the case that gentle slopes are gentle because they are underlain by weaker materials, and may even be the parts of the slope where landslides have actually occurred. Conversely, steep slopes are not necessarily unstable; they can reflect the presence of stable strong bedrock close to the surface.

- This study has as its primary focus the development of a overall slope process model, in which observed process rates are described in probabilistic terms. This is essential to understand clearly the nature of the hazards and the probability of their occurring. The model is not based on deterministic calculations of stability or factor of safety, but is rather an empirical, observation-based model.

5 THE INVESTIGATION

5.1 Field Studies

The investigation commenced with a limited literature search by Marion Leiba in Canberra, and the viewing of some aerial photographs covering the study area at a scale of 1:25 000 and the interpretation of those photographs by Fred Baynes at his home office in Perth, WA. Unfortunately the aerial photographs were printed from digitised imagery and the pixel size was evident when viewed under high magnification in a stereoscope. Consequently detailed geomorphological interpretation from the photographs was difficult.

The field studies commenced on 2 March 1997 when Fred Baynes and Marion Leiba went to Cairns and carried out:

- an overall reconnaissance of the area over several days;
- an examination of some 1:4000 aerial photographs;
- a detailed compilation of relevant historical data;
- brief inspection of most of the areas subject to landslide risks, and the compilation of a geological/geomorphological map (landslide data map) at a scale of 1:25 000 to present the hazards; and
- preliminary mapping of one area and confirmatory inspection of mapped boundaries in another, to initiate the process of verifying the general landslide model depicted in the 1:25 000 map.

The initial field studies were completed on 19 March 1997.

A follow up visit was made between 8 and 11 April 1997 by Marion Leiba to assess the impacts of Cyclone *Justin* which hit the Cairns area on 22-23 March 1997.

Marion Leiba re-examined the debris flows on 12 and 13 June 1997.

On 11 February 1999, Cyclone *Rona* crossed the coast north of Cairns, and Cairns airport received 296 mm of rain in 24 hours. Marion Leiba examined the effects of this cyclone between 24 and 28 February 1999. During the period 15-18 April 1999, she documented the effect of prolonged heavy rain in February-March 1999. These two field trips were to assess the landslide response against the developing model.

It should be noted that, considering the size of the study area and the complexity of the geology and geomorphology, only a relatively brief field study was involved in the assessment. Consequently, the boundaries of the geomorphological units on the landslide data map are provisional in nature and have been tentatively plotted to an accuracy of ±100m.

5.2 Office Studies

Prior to the office studies the hazard map was digitised and the catalogue of events was prepared. Office studies, during which Fred Baynes worked with Marion Leiba and Greg Scott, were carried out in Canberra between 5 May and 16 May 1997 and included the following activities:

- development of a GIS based hazard analysis and assessed risk presentation system;
- development of a risk assessment framework;
- presentation of that risk assessment framework within the GIS system;
- documentation of the process and compilation of the provisional report; and
- discussions of the same with Alan Moon, formerly of Golder Associates.

The aim of this approach was to develop a robust assessment framework, which could be extended at a later date if necessary.

Following the office studies in Canberra, effort was directed towards developing a generic risk assessment methodology and refining the interpretation of the process rate relationship. These efforts were compiled in a draft report.

This was reviewed in the field by Alan Moon, accompanied by Fred Baynes and Marion Leiba, during the period 28 July to 4 August 1997. Alan Moon's comments are attached at Appendix A.

Since then, Marion Leiba and Greg Scott have further refined the recurrence relationships, risk calculations and risk maps. The report has been modified to take this work, most of Alan Moon's review comments, and referees' comments into account.

6 SLOPE PROCESSES, LANDSLIDE DATA AND OBSERVATIONS

6.1 Slope Processes

The landscape around Cairns City is dominated by a series of escarpments which are developing by scarp retreat. The scarp retreat is caused by weathering, erosion and removal of debris from the slope by slope processes, which take two main forms:

- On steeper bedrock slopes, and bedrock slopes masked with relatively thin colluvium, weathering and erosion leads to fast moving landslides (usually rock falls, rock slides, debris slides, and debris flows) confined to the hill slopes. By this process rock and soil moves down slope under the influence of tropical rainstorms.

- During the more extreme rainfall events, the combined effect of multiple landslides in the upper parts of gully catchments, and the remobilisation of accumulations of debris in the major gully systems, periodically results in large debris flows which flow onto the depositional plains at the base of the bedrock slopes.

These slope processes are illustrated in Figure 5. Definitions of geomorphic units (b1, b2, etc) are presented in Table 4.

It is conceivable that locally some form of rotational or translational slides could happen in the accumulated fan debris where such deposits are themselves undercut by erosion. Small batter failures were observed in this material after Cyclones *Justin* and *Rona*. Such processes have not been considered further in this preliminary assessment.

Landslides in the walls of trenches and cuttings in the plains have also not been considered in this study, but it must be remembered that this sort of failure can, and does, cause fatalities. On 31 May 1900, the landslide with the fourth largest recorded number of Australian landslide fatalities happened in Cairns. Five men were killed and one buried alive for ninety minutes when an 8 m-deep tramway cutting they were constructing at Riverstone for the mill at Gordonvale caved in. The location was at "Dead Man's Gully" or "Dead Man's Cutting" (A. Broughton, Cairns Historical Society, written communication, 1999), in a river terrace in Gordonvale, 3 km WNW of Walsh's Pyramid (Figure 1). The cutting was partly bulldozed in the 1980s, but the upper portion of the northern wall is still visible (Plate 1).

No evidence of other forms of landslide was obtained during the study. In particular, *there was no record of any deep-seated, slow-moving landslides having occurred.* The landslides observed tend to be shallow (Appendix C).

Both Hoffman (1984) and Natural Resource Assessments Pty Ltd (1997) assert that, for slopes with the same angle, those underlain by granitic rocks tend to be less stable than those underlain by metamorphic rocks. Our study does *not* indicate that granite terraines are more susceptible to landslide than areas underlain by metamorphic rocks, either for large debris flows or for batter failures on the hill slopes.

The presence of debris flows and fan complexes of debris was recognised in the

1:100 000 geological map of the area and assigned a Pleistocene age, 1.8 million - 10 000 years before present (Queensland Department of Mines, 1988). However, there have been one confirmed and at least two probable large debris flow events in the Cairns area since European settlement.

In 1951, there was a large relatively rapid debris flow event just north of Buchan Point near Ellis Beach (Figure 1) when up to 3 m of debris accumulated on the Captain Cook Highway at various points along a 10 km section during one rainstorm (Bird, 1971; *Cairns Post*, 15 January 1951). A contemporary newspaper record of this event is presented in Appendix B.

The probable debris flow events happened in 1878 and 1911 on the eastern side of Trinity Inlet. Deposits from numerous debris flows have been identified in this area (Queensland Department of Mines, 1988; and our field observations). On 8 March 1878, a "flood" followed by a severe cyclone triggered many landslides across the Inlet. They could be heard distinctly in Cairns (Jones, 1976). On 1 April 1911, a big landslide occurred in the Nisbet Range (Figure 1), also across the Inlet from Cairns. The scar could be seen in photos for several years afterwards (A. Broughton, Cairns Historical Society, personal communication, 1997). This landslide "brought away trees, rocks and everything else from a considerable distance up the mountain side" (*Cairns Post*, 3 April 1911).

On the basis of this information, and observations made in the field (see below), it is considered that some of the debris flows could be relatively recent, and thus represent a potential threat to the community.

6.2 Landslide Data Map

Based largely on the interpretation of aerial photographs and existing geological mapping, together with the model of slope processes, field inspection, and historical research, a map (Figure 6) was created of the study area at a scale of 1:25 000. Table 4 provides a description of the geomorphic units portrayed on the map together with an explanation of the nature of the hazards associated with each geomorphological unit. Individual landslides marked in the map are from the landslide database (Appendix C).

The geomorphological units presented in Figure 6 are interpreted from aerial photographs and have only been subject to very limited verification on the ground.

The boundaries of the geomorphological units are provisional and have been plotted to an accuracy of ±100m. Consequently the risk maps derived from it also have this limitation. Polygon boundaries are approximate only and some details on the landslide data map may change with further and more detailed field work. For detailed site-specific assessments, our broad findings should be checked by geotechnical specialists.

Map colours have been chosen to highlight the debris flows, represented by the units, fc, fp and fd.

The proximal portion (fc and fp) is that part of the debris flow closer to the source of the landslide. The coarsest part of the debris flow, closest to its source, is fc, the massive core. It has an irregular lobate surface and contains numerous boulders 1 m or more in size in a matrix of finer material. It grades into fp, debris flow fan material with gently undulating convex slope forms.

Further again from the source, this grades into fd, the distal portion of the debris flow. It is more gently sloping and contains finer grained sediments. Debris flows, though classified as landslides, can contain up to 50% water and, after they deposit some of their solid material, can grade into flash floods. The distinction between debris flow and flood deposits may not be clear, as floods often also transport sediment. On the map, a2 is similar to fd but does not have an obvious major debris flow source.

6.3 Landslide Database

The Cairns landslide database was compiled from field observations in February and April 1997, from discussions with Cairns residents, from examining contemporary newspapers, and from literature searches in the Cairns Historical Society Library and the Cairns Public Library. Details of the catalogue of events are presented at Appendix C. References are listed at the end of the Appendix.

6.4 Site Specific Observations

To verify aerial photo interpretation and to collect data on slope process rates, field examination of certain debris flow deposits, and logging of failures along Lake Morris Road and Kuranda Range Road, were carried out in more detail than for the area as a whole, and a working hypothesis put forward for the relative ages of large debris flows in the Cairns area. Small landslides in the suburbs were also observed.

6.4.1 *Age of Debris Flows*

The absolute age of debris flows could only be established when, as in the case of the 1951 Ellis Beach event, there was a historic record. Others are undated. The relative ages of some debris flows were inductively inferred from the following lines of reasoning:

Debris flows in the Cairns area appeared to be distinguishable into four classes, listed below in order of increasing age, based on the degree of weathering of the matrix and of the clasts (boulders or cobbles of granite and/or metamorphic rock):

- deposits with surfaces devoid of topsoil, but with some tree and scrub growth, assumed to be several decades old, as seen in the 1951 Ellis Beach event deposits. Similar surface characteristics were observed in parts of the South Redlynch debris flow complex;

- deposits with unweathered clasts and a grey brown matrix, assumed to be Holocene in age (less than 10 000 years old), as seen in the 1951 Ellis Beach event deposits and in parts of the South Redlynch fan;

- deposits with unweathered clasts and a characteristic red brown matrix, possibly due to iron accumulation, assumed to be perhaps late Pleistocene, i.e. between about 50 000 and 10 000 years old. This class of deposit may represent the bulk of the larger fans at Redlynch, which were interpreted as being of Pleistocene age in the Geological Survey mapping. In this respect it is relevant to note that studies of late Quaternary geomorphological events in the tropics suggest a period of more active mass movement at the Pleistocene/Holocene transition (Thomas & Thorp, 1995); and

- deposits with completely weathered clasts, assumed by analogy with deposits containing weathered clasts from elsewhere to be perhaps 50 000 to 500 000 years old.

The age sequence suggested above is just a working hypothesis for the Cairns area, as the composition of both the matrix and clasts of a debris flow depends on its provenance.

However, debris flow deposits from all four categories above were observed in the large South Redlynch fan, which appears to have accumulated over a long time period from a number of debris flows, presumably from the same general source areas. It is probable that completely weathered boulders would disintegrate during transport in a debris flow, so it is reasonable to assume that they weather *after* debris flow deposition, and that a deposit with completely weathered boulders is older than one with relatively unweathered boulders.

Partial support for the relative ages suggested also comes from the following observation. In the vicinity of Alexandra and Houston Streets, behind Palm Beach (Figure 1), material with a grey-brown matrix (similar to the 1951 Ellis Beach deposits) and fresh-looking clasts up to 300 mm long, overlies material with a red matrix and clasts up to 100 mm long. Consequently, at least in this case, the deposit with the grey-brown matrix is younger than that with the red matrix.

6.4.2 *South Redlynch Debris Flow Complex*

The debris flow complex south of Redlynch Post Office (Figures 1 and 6) was mapped at a scale of 1:5000. This map is presented in Figure 7. Of particular note are the following:

- There is abundant field evidence that there have been a succession of large debris flows in this area (Plates 2 and 3), with boulders several metres in diameter being carried down from the slopes in flows that must have been several metres thick in their proximal portions (Plate 4).

- The interpreted age of parts of the fan complex is less than 1000 years and, as debris flows have been occurring in the area for possibly tens of thousands of years, it is likely that debris flows of similar magnitude could occur in the future. Field observations suggest that concrete may be incorporated in the debris deposit in the creek bed west of Harvey Road. However, none of the boulders lie on top of the pieces of concrete, so the latter may have been deposited during subsequent floods. If they are part of the debris flow deposit, then flows have occurred since European settlement.

- The area is crossed twice by the Kuranda railway, with culverted embankments and steep cuts, and development has extended upslope to the upper railway crossing. There is the potential for slope failures involving debris flow, blocked culverts, and embankment collapse, which could possibly impact on the community.

- The field mapping was only very limited in scope in that there was no access to properties; it was carried out from existing rights of way in a limited time.

- The subdivision development in this area probably involves a degree of slope grooming. From discussions with builders in the area, boulders are taken from building blocks during the early stages of development for use as architectural features or retaining walls on building blocks at later stages of development. This results in a distortion of the field evidence available to support interpretation of the age and/or presence of debris flows.

Note that, immediately to the north of this area, there is a similar sized debris flow complex, with the Redlynch shopping centre (see Figure 1 for the location of the post office in the shopping centre) in its distal part, that has not been inspected in any detail. However some exposures, with a reddish matrix, suggest that the debris accumulations occurring in this northern fan complex may be older than some in the South Redlynch fan. The deep incision (Figure 6), to the west of Harvey and Daphne Streets, could act as a conduit for debris flow activity at a lower part of the slope.

6.4.3 *Ellis Beach Complex*

This is the area that was described in the 1951 newspaper article presented in Appendix B.

The debris is visible to this day on the landward side of the Captain Cook Highway behind Ellis Beach (Plate 5), and large boulders, as well as pieces of concrete entrained in these debris flows, can still be seen on the beach (Plate 6). The following comments are considered to be relevant.

The Captain Cook Highway in this area is built immediately below, and in some places cut into, the escarpment. It was completed in the 1930s and consequently is one of the few elements at risk in Cairns which has been exposed to proximal debris flow hazard for more than 50 years.

The debris flows originated when about 700 mm of rain fell in just under 5 hours on 12 January 1951. The event blocked the Captain Cook Highway over a distance of 10 km. Accumulated debris included boulders several metres in diameter and covered the road to a depth of over 3 m, according to local reports. The road was blocked for about two weeks and ultimately in places was rebuilt above the level of the old road.

A scientific paper by Bird (1973) discusses the debris flows as an example of a catastrophic event, clearly documented in recent historical times. From the perspective of this study, this event is clear evidence that large debris flows could occur in the Cairns region with the potential to impact upon communities.

6.4.4 *Bayview Heights*

A debris flow complex in the Toogood Road - Sydney Street area of Bayview Heights (Figure 1) was mapped and the details of the boundaries are presented in Figure 8.

In the proximal part, relatively unweathered bouldery material, containing boulders up to 2 m long, has been deposited on top of older, less coarse material with a red matrix. This suggests at least two episodes of debris flow formation.

It is important to note that the downstream natural boundary of this complex has not been established and may include part of the Bayview Heights development.

6.4.5 *Smithfield Heights*

In Smithfield Heights (Figure 1) what appeared to be a debris flow deposit was inspected in the creek bank immediately east of Chatham Terrace (off Stanton Road). There appear to be two debris flows of different ages.

The younger one consists of boulders up to 1.5 m long. These rest on top of what may have been older debris flow material - a layer several metres thick of boulders up to 400 mm long in a reddish brown matrix.

6.4.6 *Small Suburban Landslides*

Instances of landsliding have been recorded in the existing suburbs, either on cuts behind houses, or road cuts (Plate 7), or fills constructed for roads. Those logged during field work in March 1997 before Tropical Cyclone *Justin*, and after *Justin* in April 1997, are listed in Appendix C.

In 1990, during Tropical Cyclone *Joy*, presumed erosion of a creek bank below a road caused a landslide which severed the traffic connection between Granadilla Drive and Comet Steet, Bayview Heights. These two roads are now connected only by a footpath (Plate 8).

Batter failures triggered by rain from Tropical Cyclone *Rona* in February 1999 were observed in Toogood Road and Sydney Street (Bayview Heights), Chirio Drive (Freshwater Valley), and Stoney Creek Road (Kamerunga).

During the period 27 February to 20 March 1999, approximately 800 mm of rain fell in Cairns. This triggered a number of small landslides in suburban areas, including four affecting house blocks, and one on the shoulder of Granadilla Drive.

The Granadilla Drive landslide, on the Earlville-Bayview Heights boundary, is about 50 m northeast of the 1990 slip, mentioned above. It is a debris slide with a 1m-high, 30 m-wide head scarp in the far edge of the outer footpath and the debris has run down to the creek below. The volume of debris is estimated to be 150 m^3. There is a few centimetres subsidence and minor cracking in the road behind the scarp.

Of the four landslides affecting house blocks, two were in b3 areas of Earlville and Woree, and two were in b2 areas of Bayview Heights and Whitfield.

The Earlville landslide was a slump-debris flow with an estimated volume of 30 m^3 in an non-engineered batter behind a back yard swimming pool affected by the toe of the landslide.

The Woree landslide was also a slump, but it did not run out and affect the adjacent house because a retaining wall of sleepers and girders, already in place, had contained it.

The Bayview Heights debris slide happened after several days of heavy rain in March 1999 and had a volume of about 20 m^3. It was in a steep road batter below, and in front of, a house. It had undermined a wooden deck. Another minor debris slide had occurred in the road batter a few metres away, but this had not affected any house blocks.

The Whitfield landslide was in a batter behind a house and happened in March 1999 (Peter Agar, Cairns City Council, personal communication, April 1999). It was not examined in the field by Marion Leiba.

The following comments concerning landslides in the established suburbs are relevant:

- most of the landslides appear to be associated with cuts resulting from development of the area;

- virtually all of the small landslides that were observed appear to be related to weak relict structures in bedrock, to fill, or to very steep cuts in colluvium; and

- most of the landslides are less than 100 m^3.

6.4.7 *Landslides along Arterial Roads*

Tropical Cyclone *Justin* affected Cairns on 22-23 March 1997.

Landslides were logged along Lake Morris Road both before and after *Justin* (Appendix C). Twenty-one batter failures and two fill failures occurred along Lake Morris Road during the 1996-1997 wet season prior to *Justin*, compared with 52 new batter failures after *Justin*.

Forty-six new batter failures (Plate 9) and one new fill failure were logged along Kuranda Range Road after *Justin*, and batter failures were noted along other roads in Cairns (Appendix C).

Tropical Cyclone *Rona* crossed the coast on 11 February 1999.

Thirty-eight new landslides (mainly rock slides, debris slides, and small debris flows) were logged in the batter along Kuranda Range Road after *Rona*. They had a total volume of about 237 m^3. The volume of the largest was about 50 m^3.

It was not possible to log landslides along Lake Morris Road after *Rona* because the road was closed due to landslides. However, a fill failure at the edge of the road, about 100 m beyond the barrier near the lookout, had become a debris flow, with an estimated volume of 60 m^3, which appeared to have travelled almost to the base of the escarpment.

Small debris flows and slides triggered by rain from Cyclone *Rona* were visible in the batter of Barron Gorge Road. A large presumed debris flow had deposited a considerable quantity of mud in a dip in the road, 2.9 km from the power station end of the road. Marion Leiba observed this mud still being removed by the truckload 13 days after the cyclone, when the road had already been reopened. A Queensland Main Roads supervisor subsequently told her that the mud had come down through the trees onto the road without knocking the trees down. No photos or other information were available from which to estimate the volume.

A number of batter failures triggered by rain from *Rona* were also observed in Reservoir Road (south of Whitfield), Brinsmead-Kamerunga Road, and Redlynch Intake Road. They had estimated total volumes of 10-15 m^3, 2 m^3, and 19 m^3 respectively. Individual landslide volumes varied from less than one to 2 m^3 in Reservoir Road, and 1-4 m^3 in colluvium along Redlynch Intake Road.

North of the study area, rain from *Rona* triggered a rock fall/rock slide that attracted media attention. It blocked the Captain Cook Highway about 19 km north of Ellis Beach, between Cairns and Port Douglas, with an estimated 160 m^3 of granitic debris, including boulders 1- 2 m in size.

During the 27 February to 20 March 1999 rains, a number of batter and fill failures (Plate 10) were triggered along Lake Morris Road. Two batter failures with estimated volumes of 4 m^3 and 500 m^3 (Plate 11) respectively happened near the Smithfield end of the Kuranda Range Road at the start of this period. The latter subsequently enlarged to a volume of 1500 m^3 (Golder Associates, personal communication, 1999). Three small probable debris flows were observed along the Barron Gorge Road. One of the batter failures on Reservoir Road triggered by rain from *Rona* had enlarged from 2 to 4 m^3 as a result of the subsequent rain.

In April 1999, six minor batter failures (debris slides and falls) were logged in colluvium along the Yarrabah Road on the eastern side of Trinity Bay. Their estimated total volume was only 3 m^3. It is not known whether they were triggered during *Rona* or in late February-March 1999, as the road was inaccessible from Cairns in late February 1999, due to flooding.

Along the Gillies Highway, south of the study area, numerous debris slide and rock slide batter failures were observed by Marion Leiba in April 1999. These had occurred probably during *Rona* and the February- March 1999 rains. A fill failure, with a width of about 50 m measured parallel to the road, in the Gillies Highway beside the Mulgrave River, had happened during *Rona*.

7 QUANTITATIVE LANDSLIDE RISK ASSESSMENT

The terms used in the risk assessment are summarised in Appendix E.

7.1 GIS Landslide Risk Polygons

The landslide risk assessment was carried out using a GIS so it was necessary to select polygons, based on the slope process model, for which to calculate the landslide hazard, and to interrogate for numbers of elements at risk in order to calculate the total risk. These polygons could then be used to produce GIS landslide risk maps of the Cairns area.

The GIS polygons used in the hazard and risk analysis were:

- b1, b2, and b3 – the hill slopes;

- fc, fp, and parts of other geomorphic units of the gentle slopes, below b1/b2/b3, susceptible to proximal debris flow runout; and

- fd, and parts of other geomorphic units of the gentle slopes, below b1/b2/b3, susceptible to distal debris flow runout.

The polygons b1, b2, b3, fc, fp and fd are defined in Table 4 and shown in Figure 6. Additional areas which may be susceptible to debris flow runout were delineated as discussed below.

7.2 Debris Flow Runout and Shadow Angles

A debris flow originating in one geomorphic unit can extend and impact on the unit downslope. The extent of any impact may be conveniently defined by the shadow angle relevant to that process (Hungr, 1997; Wong *et al*, 1997). The shadow angle is the angle between the horizontal and a line drawn from the limit of the proximal or distal part of the debris flow to the top of the escarpment. It is measured in the field using a clinometer. The shadow angle concept is illustrated in Figure 9.

Based on field observations and information available in the literature, the details of which are presented in Appendix D, shadow angles of 19° and 14° were chosen to represent the limits of the proximal and distal portions respectively of potential debris flows.

Using a GIS, the extent of areas covered by shadow angles of 19° and 14° extending from scarp crests or ridge lines have been incorporated to define hazard zones on the gentle slopes below the bedrock systems. These zones represent the limit to which a debris flow might conceivably extend were it to originate high in the catchment of a particular gully system. The extent of the shadow angle hazard zones is illustrated in Figure 10. The polygons thus defined may be thought of as being at some risk from debris flow.

These shadow angles were then checked by doing a GIS plot of predicted debris flow runout superimposed on the Cairns landslide data map. The overall fit appeared reasonable, overestimating in some areas and underestimating in others the runout distances suggested by units fc, fp and fd in Figure 6.

We have assumed uniform shadow angles for the limits of the proximal and distal portions of debris flows throughout the study area. The assumption implicit in this is that the runout distance of debris flows is greater for higher escarpments, and depends only on the height of the escarpment, not on the volume of source material available to be incorporated in the landslide, nor the height on the escarpment at which the landslide originates.

7.3 Landslide Recurrence Intervals

For the purpose of deriving recurrence intervals for landslide events of various minimum volumes, two processes were considered.

First were the landslides originating on the hill slopes and affecting the landslide hazard in the b1, b2 and b3 polygons. For the purposes of this regional pilot study, they were considered to have a uniform rate of occurrence in these polygons throughout the map area. The recurrence rates were derived from observations of landslides on *roads and developed slopes* and so are only applicable to hill slopes that are undergoing development. This was considered appropriate, as one of the uses of the maps is to be as a planning tool for the Council. Also, there are insufficient data available for natural slopes to do quantitative work. The logarithm of the failure volume (m^3) per 10 km of the escarpment was used as a measure of landslide event magnitude. The length, 10 km, was chosen arbitrarily. A landslide event was taken to be the suite of landslides triggered by a single rainfall event. As a simplifying assumption, the b1, b2 and b3 polygons were all assumed to be equally susceptible to slope failure and to be subject to the same recurrence relation. The derivation of the recurrence relations are given in Appendix F.

The second process was the occurrence of debris flows large enough to run out on to the plains. Examples are those, described earlier in this report, in the Ellis Beach area, in Freshwater Valley (Figure 1), and at Bayview Heights. Because of their runout, they may constitute a landslide hazard in flatter areas where landslides would not normally be considered a problem. For the 10 000 year rainfall event, these were assumed to occur in all gullies throughout the area. For smaller rainfall events, only one or two debris flows may occur in the map area. Their frequency was calculated for the whole of the map area, then reduced proportionately to consider only 10 km of escarpment. The logarithm of the failure volume (m^3) was taken as a measure of the magnitude of the debris flow event (a suite of debris flows triggered by a single rainfall event). The derivation of the recurrence relation is given in Appendix G.

In summary, magnitude-recurrence relations per 10 km of escarpment were established for:

- the total volume of a set of landslides triggered, by a rainfall event, along roads and the railway up the escarpment (Figure 11(a));
- the total volume of a set of landslides triggered by a rainfall event on fully developed slopes (Figure 11(b)); and
- the total volume of a family of debris flows which extend on to the plain and were triggered by a single rainfall episode (Figure 12).

7.3.1 *Assumptions in Deriving Recurrence Relations*

- The 10 000 year event plotted in the landslide recurrence interval graphs involves torrential rain over the entire area, causing debris flows in all gullies, and that one fifth to one quarter of the b1/b2/b3 area not involved with large debris flows is affected by other landslides; and

- to derive a recurrence relation for fully developed slopes from logs along roads and the railway, assume that the entire area is developed with a network of roads 100 m apart, and without mitigation measures such as retaining walls.

7.4 Landslide Hazard Assessment

The recurrence relations discussed above relate the logarithm of the volume of a landslide event (landslide magnitude) to the number of landslide events per year per 10 km of escarpment with volumes greater than or equal to the plotted volume. The landslide event volume would be the *maximum* volume of a single landslide triggered by the rainfall event - often a landslide event consists of several smaller landslides, rather than one large one.

7.4.1 *Methodology*

The method of calculating hazard and risk from a magnitude recurrence graph is shown schematically in Figure 4.

If N_1 is the number of events per year per 10 km of escarpment with volume greater than or equal to v_1, and N_3 is the number of events per year per 10 km of escarpment with volume greater than or equal to v_3, then N_1–N_3 is the number of events per year per 10 km of escarpment with volume between v_1 and v_3.

For the hazard calculations, the logarithm of the volume was divided into intervals of 0.5, that is 1.5, 2.0, 2.5, 3.0, 3.5,...... These correspond to volumes of 32, 100, 320, 1000, 3200,....... m^3. Thus the ranges of volumes in the hazard calculations are 32 to 100, 100 to 320, 320 to

1000, 1000 to 3200,....... m^3. The hazard posed by landslides in each volume range was calculated in the manner described below and is shown in Tables 5, 6 and 7, which are the worksheets used for the calculations. The hazard values for each volume range were then summed to get the total hazard.

7.4.2 *Calculation of Hazard Contribution from each Volume Range*

The volumes corresponding to the mid points of these ranges on the log graph are 56.2, 178, 562, 1780, 5620,...... m^3. If the mean thickness of the landslide is t (m), then the areas (Ai) of impact of landslides of volume 56.2, 178, 562, 1780, 5620,...... m^3 are 56.2/t, 178/t, 562/t, 1780/t, 5620/t,...... m^2.

If At is the total area of the geomorphic unit, the hazard of which is under consideration, then the area per 10 km of escarpment is A10 = At multiplied by 10/122, because the escarpment in the map area is approximately 122 km long.

Given that a landslide, or suite of landslides triggered by the same rainfall event *does* occur, then the probability (Pi) of impact of a landslide of area Ai at any point of the geomorphic unit under consideration is Ai/A10. This is because the recurrence relations were derived for 10 km of escarpment.

The probability of impact per year of at least one landslide in a given volume range at any point of a geomorphic unit under consideration is approximately Pi multiplied by Nr, where Nr is the number of landslide events per year per 10 km of escarpment in that volume range.

7.4.3 *Calculation of Total Hazard Contribution from Volume Ranges under Consideration*

The hazard for the geomorphic unit under consideration is the probability per annum of at least one landslide impacting a point in the polygon. It is calculated by adding together the probability of impact, at a given point in the study area, of landslides in each of the volume ranges.

The landslide hazard calculated by the method outlined above may be an *over-estimate* because the hazard calculations do not subtract the probability of a point in a polygon being hit by more than one landslide in a year.

Probability of landslide impact at a particular point during a project life of, say, 100 years, would be 100 times the annual hazard value.

7.4.4 *Hill Slopes*

Table 5 shows the calculations for landslides impacting on b1, b2 and b3, the slopes of the escarpment. A typical thickness of 1.5 m was chosen for landslides on b1/b2/b3 hill slopes.

This thickness is an *estimate* based on field observations, but nearly all recent (1997-1999) landslides observed in b1/b2/b3 have been low-volume, so the thickness of large ones is uncertain. The hazard values for the currently undeveloped parts of b1, b2 and b3 are *predictive* values, as they give the probability per annum of impact of a landslide at any point in these polygons if it were to be developed. The hazard value obtained is 0.00016 (1 in 6000), or 0.0002 when rounded to one significant figure. It would be expected to be less on slopes developed with appropriate geotechnical investigation before, and good engineering practice during development, because landslides in developed areas in Cairns are often batter or fill failures. It would also probably be less on undisturbed slopes, but there is insufficient information at present to know how much less it would be.

7.4.5 *Proximal Parts of Debris Flows*

Table 6 shows the calculations for areas which may be impacted by the proximal portions of debris flows (including fc). The area of impact was calculated assuming a mean thickness of 2 m, and that half the debris flow volume is retained in the proximal portion. (The other half flows on and becomes the distal portion of the debris flow). The areas assumed to be susceptible are those where proximal portions of debris flows have been mapped (fc and fp, defined above), plus those parts of the plain at the base of the escarpment within the 19° shadow angle. These susceptible areas include parts of the polygons a2, a3, ac, af and as (various kinds of deposits of alluvium). The hazard (the probability of a point being impacted by a debris flow) was calculated to be 0.00012 per annum (1 in 8000), or 0.0001 when rounded to one significant figure.

7.4.6 *Distal Parts of Debris Flows*

Table 7 shows the calculations for areas which may be impacted by the distal portions of debris flows. The area of impact was calculated assuming a mean thickness of 0.6 m, and that half the debris flow volume is in the distal portion (the other half having been already been deposited in the proximal portion). The areas assumed to be susceptible are those where distal portions of debris flows have been mapped (fd, defined above), plus those parts of the plain between the 14° and 19° shadow angles. Susceptible areas include parts of the polygons a2, a3, ac, af, as and d2. The hazard (probability of a point being impacted by a debris flow) was calculated to be 0.00011 per annum (1 in 9000), or 0.0001 when rounded to one significant figure.

7.4.7 *Assumptions in Hazard Assessment*

- a uniform process rate across, and from top to bottom of, the entire escarpment, irrespective of local geomorphology, rock type, soil cover or position on the escarpment;

- the escarpment is developed, with a network of roads, but without mitigation measures such as retaining walls;

• uniform shadow angles for debris flows (19° for the proximal part, and 14° for the distal part). This implies that the runout distance of debris flows is greater for higher escarpments, and depends only on the height of the escarpment, not on the volume of source material, nor the height on the escarpment at which the landslide originates; and

• in debris flows, half the volume of solids is deposited in the proximal part, and half in the distal part.

7.5 Landslide risk assessment

7.5.1 *Intensity Relationship*

The relationships in Figures 11(a), 11(b) and 12 are magnitude/recurrence interval relationships for the two main landslide types. In an analogous way to earthquakes, the magnitude is the size of the event, the intensity is the damaging effects of that event at any particular point. It is therefore necessary to think about what is the intensity of the event within any particular part of the landslide system.

In the case of the landslides and debris flows in source areas (b1/b2/b3), and as a first approximation, it is assumed that the intensity does not vary within the body of the landslide and is defined by the boundary of the landslide, *i.e.* the intensity is uniform across the landslide.

In the case of the larger depositional debris flows, each event has been subdivided into a proximal and a distal portion. As a first approximation, it is assumed that the intensity, while differing between the proximal and distal portions of the debris flow, is defined by the boundary of the landslide. The intensity is assumed to be uniform across the proximal or the distal portion of the landslide. This is a simplifying assumption considered to be reasonable for a preliminary assessment.

7.5.2 *Vulnerability of b1/b2/b3 Elements to Landslides*

In the Australian landslide database and Cairns landslide database there are 24 landslides, which impacted buildings, and which may be equivalent to the b1/b2/b3 landslides in Cairns. In 11 of these, no buildings were destroyed, giving vulnerabilities of 0 in these cases. In 11 cases, all the buildings were destroyed (the number of buildings per landslide varying from one to three), so the vulnerability for these is 1.0. For the remaining two out of the 24 landslides, two out of 16 and three out of seven buildings were destroyed, giving vulnerabilities of 0.1 and 0.4 respectively. The mean vulnerability of buildings for the 24 landslides is Vs = 0.5. This may be a conservative value, because there could be cases where buildings were impacted by landslides and not destroyed which have gone unreported. Assuming that only half the cases were reported in the database, then Vs = 0.25.

In three of these 24 landslides, people were killed. At Walhalla in Victoria, all two people were killed, giving a vulnerability of 1.0. At Coledale, NSW, two out of five people were killed, giving a vulnerability of 0.4. At Thredbo, NSW, 18 out of 19 people were killed, giving a vulnerability of 0.9. For the remaining 21 landslides, either no people were in the buildings, or else they were not killed, giving a vulnerability of 0. This gives a mean vulnerability for the 24 landslides of Vp = 0.1. This value could be conservative because landslides which cause death are more likely to be reported than those which do not, and because fill failures were the cause of two of these landslides. Assuming that only half the cases were reported in the database, then Vp = 0.05. This figure is in good agreement with the value suggested by Wong *et al*, 1997, for the vulnerability of a person in a building if debris strikes the building. As it is derived from figures relating to buildings impacted by landslides in the database, it takes into account the fact that buildings may not be occupied all the time.

The data in the Australian landslide database are not detailed enough to calculate a vulnerability for roads. However, Cairns City Council informed us that Kuranda Range Road is totally blocked about once a year, but needs partly remaking no more than once in two years. This gives a vulnerability of no more than 0.5. Lake Morris Road gets totally blocked about three times a year, but needs partly remaking at most once every two years. This gives a vulnerability of at most 0.17. The mean of 0.5 and 0.17 is 0.3, so 0.3 was taken as the value of the vulnerability, Vr, of roads.

For the calculation of the risk of a road being temporarily blocked by a landslide, the vulnerability of the road is 1, provided that the landslide is large enough to spread debris across it.

7.5.3 *Vulnerability to Debris Flows*

There are insufficient data in the Australian landslide database to calculate the vulnerabilities of people, buildings or roads to the impact of large debris flows.

Proximal debris flows

If the occupants of a house are in the path of a 3 m-high wall of swiftly moving water- laden debris then the chance of being killed may be as high as 90%. Similar values have been assumed in Hong Kong studies (Wong et al, 1997). Assuming that the occupants are there all the time during times of torrential rainfall, Vp is about 0.9. Vs and Vr would be 1, ie all housing and roads would be completely destroyed in the proximal portion of a debris flow.

Distal debris flows

The distal portion of a debris flow is taken to be a relatively shallow swift moving debris flow or sheetwash accumulation of the order of 600 mm thick. In the distal portion of the path of a large debris flow, which is a swift and powerful event, there might be a 1 in 20 chance of being killed. Assuming that the occupants are there all the time because of the torrential rain, this gives a vulnerability, Vp of 0.05. This figure is in good agreement with the value suggested by Wong et al, 1997, for the vulnerability of a person in a building if debris strikes the building. Such distal debris is unlikely to rip up roads and will just cover them most of the time so Vr = 0.3. Vs has been taken to be 0.1.

These vulnerabilities are summarised in Table 8.

7.5.4 *Specific Risk of Destruction of Buildings, People and Roads*

The specific risk of a building being destroyed is the hazard multiplied by the vulnerability. The hazard is the probability per annum of the building being impacted by a landslide. The vulnerability (Vs) is the probability of the building being destroyed if it is impacted by a landslide. "Destroyed" is taken to mean that the building is so badly damaged that it is regarded as unfit to be lived in and would be written off or demolished. It does not necessarily mean that the landslide has reduced it to matchwood or rubble.

The specific risk of an individual being killed by a landslide is taken to be the probability per annum of the *occupant of a building* being killed by a landslide. This is the probability per annum of the building being impacted by a landslide multiplied by the vulnerability, Vp (the probability of a building occupant being killed if this happened).

The specific risk of a given point on a road being destroyed is the probability of it being impacted by a landslide multiplied by the vulnerability, Vr (the probability of the road at that point being destroyed if this happens). "Destroyed" is taken to mean that the road needs remaking at that point, not that landslide material merely needs removing from its surface.

For the b1/b2/b3 hill slopes, the specific risk has been calculated and mapped for all parts of these polygons as if the whole of the polygon were developed. This is considered useful as a planning tool because, as soon as a previously natural slope is cleared and roads put in for subdivision, it is no longer a natural slope. The specific risk would be expected to be less on slopes developed with appropriate geotechnical investigation before, and good engineering practice during development, because landslides in developed areas in Cairns are often batter or fill failures. It would also probably be less on undisturbed slopes, but there is insufficient information at present to know how much less it would be.

The calculations are shown for hill slopes, proximal parts of debris flows and distal parts of debris flows in Tables 5, 6 and 7. The specific risk values are summarised in Table 9, and the maps for people, buildings and roads are shown in Figures 13, 14 and 15.

As the specific risk is an annual risk, the risk for the life of, say, a 50-year project would be obtained by multiplying the annual value by 50.

7.5.5 *Specific Risk of Road Blockage*

The specific risk of temporary road blockage by landslide debris at a point is the annual probability of a landslide occurring that is large enough to block the road at that point.

The specific risk of temporary blockage by a landslide somewhere in any 10 km length of road, parallel to the escarpment, is the probability of sufficient debris landing on the road to block both lanes.

Blockage of a road at a point

For the risk map (Figure 16), 10 m-wide roads are assumed. The volume of a batter failure necessary to block half the road, if it comes to rest at an angle of repose of about 33°, is about 60 m^3. We take this to be the minimum volume necessary to block a 10 m-wide road in b1/b2/b3 because it is likely that rocks will roll into the other lane or trees will fall across it. The probability per annum is 0.00016 (1 in 6000), or 0.0002 when rounded to one significant figure (Tables 5 and 9).

For roads in potential debris flow runout regions, we assume that the road will be blocked by debris if it is impacted by a debris flow at that point.

For roads in potential proximal debris flow runout regions we assume that the debris flow must have a minimum volume of at least 3200 m^3 to block roads and, for roads in potential distal debris flow runout regions we assume that the debris flow must have a minimum volume of 10 000 m^3 to run out and block the road. Thus the probability is equal to the debris flow hazard for debris flows greater than or equal to the minimum volume: 0.000095 per annum (1 in 11 000)), or 0.0001 when rounded to one significant figure, for points in areas susceptible to the proximal part of a debris flow, and 0.000072 per annum (1 in 14 000)), or 0.0001 when rounded to one significant figure, for points in areas susceptible to the distal part of a debris flow. These results are summarised in Table 9.

Blockage of part of a 10 km length of road

The specific risk of a temporary landslide blockage somewhere in any 10 km length of road, parallel to the escarpment, is equal to the probability of occurrence per 10 km of road of a landslide of at least the minimum volume necessary to block the road (Figure 11(a)). If this happens, the vulnerability of the road to blockage is 1.

For the risk map (Figure 17), 10 m-wide roads running parallel to the escarpment are assumed. The map depicts the estimated mean recurrence interval of a total road blockage somewhere in a 10 km length of road.

For the 60 m^3 landslide deduced in the previous section to be necessary to block a 10 m-wide road in b1/b2/b3, the mean recurrence interval is one to two years (a probability per annum of 0.6 - read from the landslide recurrence graph in Figure 11(a)).

For roads in potential proximal debris flow runout regions we assume that the debris flow must have a minimum volume of at least 3200 m^3 to block roads. The mean recurrence interval per 10 km of road parallel to the escarpment is 100 years (0.01 per annum per 10 km of road - see Table 6).

For roads in potential distal debris flow runout regions we assume that the debris flow must have a minimum volume of 10 000 m^3 to run out and block the road. From the debris flow recurrence relation, the mean recurrence interval per 10 km of road parallel to the escarpment is about 200 years (a probability of 0.004 per annum per 10 km of road - see Table 7).

For a sanity check for b1/b2/b3, the calculated risk values can be compared with actual blockage rates of Kuranda Range Road and Lake Morris Road.

Kuranda Range Road is about 10 m wide. From the recurrence relation (Figure 11(a)), a landslide with a volume of 60 m^3 or greater would be expected to happen about once every one to two years per 10 km of road (a probability of 0.63 per annum - read from the landslide recurrence graph for roads in b1/b2/b3). The length of the Kuranda Range Road up the escarpment is 11.4 km, so this would be expected to be blocked once every 17 months. In fact, the road gets totally blocked about once a year, sometimes by a single tree!

Lake Morris Road is about 6 m wide. Using the same assumptions as previously, the minimum volume of landslide required to block it is about 14 m^3. From the recurrence relation (Figure 11(a)), a landslide of this size or larger would be expected to happen about once every 6 months per 10 km of road. The road is 14.5 km long to the upper dam gate, and this length of road would be expected to get blocked about once every 4 months. This is what happens in actuality.

7.5.6 *Total Risk of Destruction of Buildings and People*

The total risk in a geomorphic polygon is the assessed number of buildings destroyed or people killed in the *developed* part of that polygon in a given period of time. It is calculated by multiplying the specific risk by the number of elements at risk. That is why it is only applicable to the currently developed parts of geomorphic polygons. These were taken to be the parts of polygons containing buildings, with a buffer zone of 50 m around each building. For this purpose, a total risk polygon is taken to be the developed part of a geomorphic polygon that is susceptible to one of the three types of landslide activity. The three types are: landslides affecting hill slopes, the proximal part of debris flows, and the distal part of debris flows. An example of a total risk polygon is the developed part of a3 between the 14° and 19° shadow angles. This total risk polygon will be the developed part of a3 susceptible to distal debris flows.

The only buildings considered in the total risk calculations were houses and blocks of flats, because these were the classes of building for which mean numbers of occupants per building could be calculated from the data in our GIS.

For buildings, the total risk for the developed part of a polygon is H multiplied by Vs multiplied by Es, where H is the hazard, Vs is the vulnerability of buildings in that polygon, and Es is the number of buildings in the developed part of that polygon. In the undeveloped parts of polygons, Es will be 0, so the total risk will also be 0. The total risk for each polygon is given in Table 10.

Because the area of each polygon is different, in Table 11 the total risk was depicted as the number of buildings expected to be destroyed in the currently developed part of each polygon per 100 years per square km of developed polygon.

A *sanity check* is provided by considering the developed part of b3. Two houses have been destroyed in this total risk polygon. The specific risk is 0.00004. The number of buildings in the polygon is 2603, giving a total risk of 0.1 per annum for the entire b3 polygon (Table 10). A discussion with D'Arcy Gallop, formerly of Cairns City Council, suggested that 15 years was about the average time that the b1/b2/b3 polygons have been settled. Thus the theoretical number of houses that would have been destroyed in the developed part of b3 is 0.1 multiplied by 15. This gives a theoretical number of houses destroyed of 1.5, compared with the actual number of two. No other houses have been destroyed by landslides in Cairns.

The polygons with the next highest total risk for houses and blocks of flats are the proximal parts, fc and fp, of debris flows (each 0.03 houses per year). The theoretical number to have been destroyed in 15 years in these two polygons is estimated to be 0.9. No houses in Cairns have yet been destroyed by large debris flows, but areas susceptible to their proximal parts have been closely settled for less than half the average recurrence interval of these events.

To assess the total risk for people, the *resident* population, Ep, of each developed total risk polygon is calculated from the average occupancy rate of houses and blocks of flats from census data and data gathered by the *Cities Project*. The mean numbers of people per dwelling were available only for houses and blocks of flats, so people in hotels, for example, were excluded. The central business district of Cairns was excluded from the calculation of the mean number of people per building because it did not include any polygons susceptible to landslide and we thought that its resident population might be atypical of suburban Cairns. The mean number of people per house was calculated to be 2.88 and per block of flats, 8.16. The total risk for people is given for each polygon in Table 10.

The total risk is highest for fp and fc (the proximal part of debris flows) where an estimated 2 people would have been expected to have been killed in the approximately 15 years that these polygons have been settled.

In fact, no-one has yet been killed by a landslide in Cairns, except for the five fatalities in a tramway cutting collapse in alluvium in 1900. The lack of fatalities is probably because of the short period of settlement of areas susceptible to landslide, and because of mitigation measures on the hill slopes. Areas susceptible to the proximal parts of large debris flows have been closely settled for less than half the average recurrence interval of these events.

Because the area of each polygon is different, in Table 11 the total risk is normalised to the number of people expected to be killed per 100 years per square km of developed polygon.

Figures 18 and 19 are the normalised total risk maps for resident people and buildings.

8 DISCUSSION

8.1 Limitations of this Study

There are some limitations (Section 4.4) that may be recognised but cannot be dealt with in this reconnaissance report:

- *the paucity of the data from which the landslide magnitude-recurrence relations were derived.* As the error bars for the data points are, in some cases, more than two orders of magnitude, errors in the risk estimates may be large (see Section 8.3);

- *lack of discrimination between the effects of shorter duration, higher intensity rainfall events, and longer duration, lower intensity rainfall events.* The data tend to be skewed towards observations after tropical cyclones, which tend to be shorter duration, higher intensity rainfall events. Cyclone *Rona* (11 February 1999) brought about 300 mm of rain in 24 hours to Cairns, following a relatively dry period. It triggered numerous very shallow landslides, with an estimated total volume of less than 1000 m^3. By contrast, during the period 27 February to 20 March 1999, over 800 mm of rain fell in Cairns, the maximum daily rainfall being 105 mm. This rainy period triggered a landslide on Kuranda Range Road with an estimated volume of 1500 m^3 (observed by Marion Leiba on 17 April 1999). It also triggered a slump on a house block in Woree that had been stable for 15 years, and other small landslides around Cairns. Clearly, the effect of prolonged rainfall, and probably of antecedent rainfall, is significant, and should be considered in future studies.

- *the regional nature of this study.* Polygon boundaries are approximate only and some details on the landslide data map may change with further and more detailed field work.

- *a uniform process rate across, and from top to bottom of, the entire escarpment profile, irrespective of local geomorphology, rock type, soil cover or position on the profile.* This will have a smoothing effect on the results, with the possible consequence that some of the higher risk areas are not specifically identified or characterised. Hazard and risk will be overestimated in some areas and underestimated in others. However, because the magnitude-recurrence relation for landslides on the escarpment was weighted heavily by observations of landslides along the Kuranda Range Road, the Cairns-Kuranda Railway and Lake Morris Road, the hazard and risk will tend to be grossly overestimated in suburban areas where mitigation measures have been put in place. Also, the effect of specific geological and geomorphological controls noted by previous studies (Hoffman,1984; Natural Resource Assessments Pty Ltd, 1997), such as the differentiation of risk between granite or metamorphic bedrock and concave or convex slopes have not been dealt with. Nevertheless, this reconnaissance study does *not* indicate that granite terraines are more susceptible to landslide than areas underlain by metamorphic rocks, either for landslides in batters on b1/b2/b3 hill slopes, or for large debris flows. However, an examination of Figure 6 does suggest that some areas, such as the escarpment behind Redlynch, have had more favourable conditions for producing large debris flows than others. This could not be investigated in this reconnaissance study.

- *a uniform shadow angle for debris flows.* The assumption implicit in this is that the runout distance of debris flows is greater for higher escarpments, and depends only on the height of the escarpment, not on the volume of source material available to be incorporated in the landslide, nor the height on the escarpment at which the landslide originates. The uniform shadow angle assumption may overestimate the area susceptible to debris flow runout in some cases.

- *the assumption that debris flow runout is not affected by the presence of large obstacles.* While very large debris flows can bury an entire settlement, smaller debris flows can be slowed when they encounter buildings, causing the landslide to deposit most of its load of boulders and thus lose much of its destructive potential – a possibility not taken into account in our analysis. This happened with the debris flow that hit the Magnetic Island International Resort in January 1998. Only units in the row furthest uphill were damaged or destroyed by boulders. These buildings reduced the rate of flow and only a few boulders were carried beyond that back row of buildings. Buildings further down the slope were affected only by water and the finer sediments that remained.

- the *lower* limit for landslide volume in the risk assessment calculations was 32 m^3;

- the assumption that vulnerability is independent of landslide magnitude;

- the assumption that landslide intensity is uniform across a landslide;

- rotational or translational slides in debris flow fans, and landslides in walls of trenches and cuttings have not been considered in the risk assessment.

Finally, the reconnaissance nature of the field mapping must again be emphasised. Polygon boundaries are approximate only and some details on the landslide data map may change with further and more detailed field work. For detailed site-specific assessments, our broad findings should be checked by geotechnical specialists.

8.2 Risk Assessment

It appears from field observations that there is a significant landslide risk in the Cairns area. On the hill slopes, the specific annual risk of road and railway blockage is high. "Because the Captain Cook Highway, Kuranda Range Road and Cairns-Kuranda Railway, which provide access to Cairns from the north and the Tableland, each pass through country with steep slopes, they may be blocked by landslides in the event of prolonged or intense precipitation. Outside the study area, the Bruce Highway and particularly the Gillies Highway (which links Gordonvale to the Atherton Tableland), may also be blocked by landslide. This makes the Cairns community particularly vulnerable to isolation by land" (Granger *et al*, 1999).

The potential threat from debris flows has not been recognised to date, and areas at risk from debris flows have been, and may be developed as subdivisions. Two examples are the Redlynch area, and the Earl Subdivision on the opposite, eastern side of Freshwater Creek (Figure 1).

This field based observation is supported by the results of the preliminary risk assessment, which indicates a specific annual risk of destruction by the proximal part of a debris flow of 1 in 8000 for a building or a section of road, and 1 in 9000 for people in houses or flats. The highest total risk of fatality from landslide is for people living in houses and flats in the proximal parts of debris flows. By adding together the unrounded total risk figures, which are quoted rounded to one significant figure in Table 10, it is estimated that a total of 16 people in the map area could die over 100 years in these areas. The specific annual risks of fatality for people living on the escarpment, and in areas susceptible to the distal portions of debris flows, are approximately 1 in 100 000 and 1 in 200 000, respectively.

The figures assessed for the specific and total risks of destruction of people and buildings in areas susceptible to the proximal parts of debris flows (Tables 9 and 10) could be questioned on the grounds that to date there have not been any people killed or buildings destroyed by debris flows in the Cairns area. In this respect it should be noted that:

- development of the higher risk areas has only occurred recently, i.e. over the past ten years;
- the typical recurrence interval is several decades for the larger, more destructive events; and
- the 1951 Ellis Beach debris flow event destroyed sections of the Captain Cook Highway over a 10 km stretch.

If no mitigation measures were in place, the total risk would be highest for buildings in the b3 (lower escarpment) polygon (Table 10). This risk has been mitigated to some extent by careful choice of house sites on the hill slopes, by drainage, and by building retaining walls.

Historical research (Appendix C, Cairns landslides – master list, events 17 and 24A) and field observation suggests that flash flooding in Freshwater Creek, or debris flows, have the potential to disrupt the Cairns water supply by blocking the intake or destroying sections of the pipeline.

8.3 Errors and Sensitivity Tests

Recurrence relation: In Figure 11(b), the recurrence relation for b1/b2/b3, the error bars for observations of landslides triggered by Tropical Cyclones *Justin* and *Rona* on the escarpment suggest that, on carefully engineered slopes in the suburbs, the hazard and specific risks for people, buildings and roads may be up to fifty times lower than the values in Table 9. This would reduce the assessed specific risk of fatality to around 1 in 5 million. If the hill slopes were developed without mitigation measures, the assessed specific annual risks for people, buildings and roads could be doubled or trebled (see the Kuranda Range Road values on the

Cyclones *Justin* and *Rona* error bars), and the specific annual risk of fatality may be around 1 in 40 000.

The widest error bar in the recurrence relation for debris flows (Figure 12) suggests that the volumes, and thus the hazard and specific risks, could be up to six times greater or less than our estimates. Hence, the specific annual risk of fatality for people living in areas susceptible to the proximal part of a debris flow could be in the range 1 in 50 000 to 1 in 2000, and for the distal part of a debris flow, 1 in 1 million to 1 in 30 000.

Vulnerability: The magnitude of possible errors in the adopted vulnerabilities is unknown. The doubling of an adopted vulnerability would double the corresponding specific risk, and a halving of the vulnerability would halve the risk. For example, if the vulnerability of buildings to the distal portion of debris flows was 0.05, not 0.1, then the specific annual risk of destruction of a building would decrease from 1 in 90 000 to 1 in 180 000. If people are assumed to occupy their houses in areas susceptible to the proximal parts of debris flows for only one third of the time, their vulnerability decreases to 0.3, and the specific annual risk of fatality to 1 in 30 000.

8.4 Acceptability of Specific Risk Estimates

The preliminary risk assessment gives the following estimates of the specific annual risk of fatality:

- on the escarpment, approximately 1 in 100 000 (1 in 5 million to 1 in 40 000);
- susceptible to proximal parts of debris flows, around 1 in 9000 (1 in 50 000 to 1 in 2000); and
- susceptible to the distal portions of debris flows, approximately 1 in 200 000 (1 in 1 million to 1 in 30 000).

These specific annual risks of fatality compare favourably with the risk from:

- smoking 20 per day, 1 in 200;
- hang gliding, 1 in 660; and
- mining, 1 in 1300.

Considering the uncertainties in the estimate, the specific annual risk of fatality from living in an area susceptible to the proximal part of a debris flow may be of the same order of magnitude as the risk from:

- driving a car, 1 in 5900;
- being run over by a vehicle, 1 in 16 000; or
- rock climbing, 1 in 25 000.

The specific annual risk of fatality for people living in an area susceptible to the distal portion of a debris flow, or on the escarpment is of the same order of magnitude as:

- dying in a plane crash: 1 in 110 000.

The landslide risks quoted above, with the exception of carefully engineered slopes on the escarpment, are all greater than those from

- lightning, 1 in 2 million; or
- meteorite, 1 in 16 billion!

The figures, other than for landslides, quoted above are from a table in Baynes, 1995.

From a consideration of the de-facto record of acceptable and tolerable annual risk criteria deduced from questionnaires and land use planning documents for potential hazards such as dams, nuclear power stations, and landslides, Fell & Hartford (1997) have suggested 1 in 1 million as a possible tolerable specific annual risk level for the *average of persons at risk* on both new and existing engineered slopes. They suggest 1 in 10 000 and 1 in 100 000 as the tolerable specific annual risk levels for the person *most at risk* on existing and new engineered slopes, respectively. For landslides on natural slopes the situation is less clear, but they think that the public may tolerate risks as high as 1 in 1000.

Using these criteria, it is possible that the specific annual risk of fatality assessed in this report for people living in areas susceptible to the proximal parts of large debris flows *may* be considered tolerable, ***provided that people are informed of the risk before they purchase property***, because the large debris flows in the Cairns area are a natural feature of the landscape. For the distal parts of debris flows, the risk is probably tolerable.

The specific risk for people living on the escarpment is acceptable, using Fell & Hartford's (1997) criteria, *if the slopes are developed with appropriate landslide mitigation measures*, as these may reduce the risk to around 1 in 5 million. If new developments took place on the escarpment without these mitigation measures, the risk could rise to about 1 in 40 000, which may not be considered tolerable under Fell & Hartford's (1997) criterion for newly developed slopes.

8.5 Acceptability of Total Risk Estimates

By adding together the unrounded total risk figures, which are quoted rounded to one significant figure in Table 10, it is estimated that a total of 23 houses and/or blocks of flats could be destroyed, and 29 of their residents killed, by landslides in the Cairns area in a 100 year period, if no mitigation measures were taken. This assumes the *present* distribution of buildings and people. *If the population continues to grow and spread into areas vulnerable to landslide, these totals could be considerably higher.*

Thirteen of these 23 buildings and eight of the estimated fatalities are on the hill slopes, and this toll could be reduced, and in many cases has been, possibly to zero, by appropriate mitigation measures with geotechnical consultation.

However, six of the 23 buildings and an estimated 16 of their residents could be destroyed over a 100 year period in areas susceptible to the proximal parts of large debris flows. A further four buildings out of the 23, and five of their residents could succumb to the distal parts of large debris flows. While risk could be mitigated by engineering works, such as levees, for the smaller of these debris flows, there is residual risk from rare, larger debris flows. This would be difficult, if not impossible, to mitigate cost-effectively.

9 CONCLUSIONS AND RECOMMENDATIONS

- General observation and the results of the preliminary risk assessment indicate that there are landslide risks in the Cairns area.

- Flash flooding in Freshwater Creek, or debris flows, have the potential to disrupt the Cairns water supply by blocking the intake or destroying sections of the pipeline.

- The greatest total risk for buildings (houses and blocks of flats) is on the hill slopes, where it is estimated that a total of 13 buildings throughout the map area could be destroyed in 100 years, *if no mitigation measures had been taken*. The mitigation measures, which may already be in place on currently developed land, could include, where appropriate, adequate drainage, retaining walls, planting of trees, and appropriate siting of buildings on properties. **Geotechnical advice is recommended for detailed site specific assessments.**

- Previously unrecognised risks are associated with the potential for large debris flows from the escarpment. It is estimated that, based on the *present* building and population distribution, a total of 10 houses and /or blocks of flats, and 21 of their residents, could perish in the runout from debris flows. While engineering works, such as levees, could be used to mitigate the risk from the smaller debris flows, there is a residual risk to people, buildings and roads from rare, very large debris flows.

- This preliminary assessment indicates that areas are being developed that may be in the path of future debris flows. Two examples are the Redlynch area, and the Earl Subdivision on the eastern side of Freshwater Creek. **It is recommended that advice concerning mitigation measures, and the development of these and other areas that may be susceptible to debris flow, be sought from geotechnical consultants with expertise in the behaviour of debris flows.**

- **Evacuation plans, to be used in the event of impending extreme rainfall events which may trigger large debris flows, should be drawn up for areas deemed susceptible. The plans should be supported by a public awareness and education campaign, addressing both the nature of the debris flow hazard and the evacuation plan.**

- **Useful contacts**

  a. **Dr.Jonathan Nott, JCU**, phone 4042 1222, to discuss the possibility of more detailed investigations, by graduate students, of areas which this reconnaissance study suggests may be cause for concern.

  b. **Public awareness and education campaigns** have been adopted successfully in the Montrose area of Victoria by the Shire of Yarra Ranges (**Lex Ritchie, Manager, Asset Management**, phone 03-9735 8467), and in the Blandswood area of New Zealand by the Canterbury Regional Council (contact **Peter Kingsbury, Hazards Analyst**, email peterk@crc.govt.nz). In both these areas, residents have chosen to live with the threat of debris flow. **Trevor Welsh**, now at City of Maroondah, phone 03-9871 0222, was Manager, Planning and Approvals, Shire of Yarra Ranges, at the time of their public awareness campaign.

10 ACKNOWLEDGMENTS

The Cairns City Council assisted with transport in Cairns and with the provision of air photos and GIS maps of the roads and cadastre in the Redlynch and Bayview Heights areas. We are particularly grateful to D'Arcy Gallop and Narelle Barton.

Cr Jeff Pezzuti, Deputy Mayor of Cairns, showed Marion Leiba landslides affecting house blocks in Cairns in the rains of February – March 1999, and landslides along the Gillies Highway. We are grateful for his time and interest.

Syd Churchill and Bob McLagan of Department of Emergency Services, and D'Arcy Gallop, formerly of Cairns City Council, helped with the logging of landslides after Tropical Cyclone *Justin*. Michelle Gatti of the Department of Emergency Services provided assistance with the logging of landslides after Tropical Cyclone *Rona*.

The Cairns Historical Society provided much information on earlier landslides. Their information was invaluable in compiling the landslides master list. Alan Broughton suggested corrections to the Cairns landslide master list, found out the exact location of the 1900 Riverstone tramway cave-in, and checked a Redlynch debris flow in the field. Mauri Gellweiler showed Marion Leiba the site of the Riverstone cave-in. We are also grateful to Graham Haussmann, formerly of Cairns City Council, for his information about early events.

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TABLE 1

Geological history

Age	
Holocene 10 000 to present	Deposition of alluvium and marine sediments at or around current sea level
Pleistocene – Holocene	Deposition of alluvium, wind blown deposits and colluvium on lower slopes and adjacent to streams
Pleistocene 1.8 my – 10 000 yr before present	Deposition of alluvium, wind blown deposits, and colluvium as various terraces, fans, cones and aprons Formation of basaltic lavas and scoria cones
Early Tertiary	Rifting of continental highland
Triassic – Permian	Granite intrusion
Devonian	Regional metamorphism, folding, cleavage
Silurian – Devonian	Deposition of muds and sands of Hodgkinson formation

TABLE 2

(a) Rainfall intensity in mm/hr for various durations and return periods

	Return Period		
Duration (hrs)	**1 Year**	**10 years**	**100 years**
1	44.8	80.2	118
12	11.6	23.0	36.4
24	7.86	15.5	24.5
48	5.19	10.0	15.4
72	3.98	7.58	11.7

(b) Selected climatic statistics for Cairns (Bureau of Meteorology, 1998)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Mean max temp (°C)	31.4	31.1	30.5	29.2	27.5	25.9	25.6	26.5	27.9	29.4	30.6	31.4	28.9
Mean min temp (°C)	23.6	23.7	23.0	21.5	19.9	17.7	17.1	17.5	18.6	20.5	22.2	23.3	20.7
Highest daily temp (°C)	40.4	38.9	37.7	36.8	31.3	30.1	30.1	31.0	33.9	35.4	37.2	40.5	
Lowest daily temp (°C)	18.2	17.9	18.6	13.0	10.1	6.2	7.3	7.8	11.1	12.4	14.6	17.1	
Av. rainfall (mm)	405	432	417	195	98	49	30	28	36	41	92	179	2001
Highest daily rain (mm)	368	286	403	186	90	70	31	63	80	87	185	230	
Av. daily sunshine (hrs)	6.8	6.1	6.4	6.8	6.4	7.5	7.3	7.8	8.5	8.8	8.6	7.7	7.4

TABLE 3

Decision Matrix - Natural Resource Assessments Pty Ltd, 1997

Slope (degrees) (%)	Disturbed Granite	Undisturbed Granite	Disturbed Non-Granite	Undisturbed Non-Granite
>33 (*c* 65)	Very High	Very High	Very High	High
18-33 (*c* 33-65)	Very High	High	High	Moderate
11-20 (*c* 19-33)	High	High	Moderate	Low
<11 (<*c*19)	High	Moderate	Low	Low

TABLE 4

Geomorphological units and potential hazards

Unit	**Hazard**
b0 - upper interfluves, creep slopes and convex creep slopes - remnants of Mesozoic peneplain	Landslide ?
b1 - fall faces or steep slopes with cliff lines, developed in bedrock	Rockfall
b2 – transportational midslopes developed as ridges and gullies in bedrock	Rockfall, small landslides
b3 – bedrock footslopes, concave or planar deeply weathered bedrock sometimes locally covered with varying thickness of clayey colluvium from one to several metres thick	Rockfall, small landslides
fc – massive core debris flow deposit with irregular lobate surface, numerous boulders greater than 1000mm	Proximal debris flow
fp – proximal debris flow fan/outwash with gentle undulating convex slope forms	Proximal debris flow
fd - distal outwash fan with uniform low angle slopes	Distal debris flow
a2 - distal outwash fan with uniform low angle slopes and no obvious major debris flow source (note that fd can grade into a2 or a2 alone can occur at the base of b3)	Distal debris flow
a3 – seasonal floodway incised into surface, possible transport corridor for debris flow	Distal debris flow grading into flood

TABLE 5

b1/b2/b3 hazard assessment calculations

Volume (m^3)	No./year that equal or exceed this volume	Volume range (m^3)	Mid-point of range on log graph (m^3)	No./year in range, N_r	Area of impact (m^2)	Prob., P_i, of impact, given that event occurs	Prob. of impact per annum $= P_i \times N_r = H_r$
32	8.45	32 – 100	56.2	5.65	37.5	0.000002	0.000014
100	2.80	100 - 320	178	1.865	119	0.000008	0.000015
320	0.935	320 - 1000	562	0.642	375	0.000025	0.000016
1000	0.293	1000 – 3200	1780	0.198	1190	0.000079	0.000016
3200	0.0945	3200 – 10000	5620	0.0636	3750	0.000248	0.000016
10000	0.0309	10000 – 32000	17800	0.0214	11900	0.000789	0.000017
32000	0.00950	32000 – 100000	56200	0.00612	37500	0.00248	0.000015
100000	0.00338	100000 – 320000	178000	0.00235	119000	0.00789	0.000018
320000	0.00103	320000 – 1000000	562000	0.000685	375000	0.0248	0.000017
1000000	0.000345	1000000 - 3200000	1780000	0.000234	1190000	0.0789	0.000018
3200000	0.000111	3200000 - 3550000	3350000	0.000011	2230000	0.148	0.000002
3550000	0.000100						

To calculate area of impact, assume a mean thickness of 1.5 m.

P_i = area of impact/area of affected polygons
= area of impact/mean area of (b1+b2+b3) per 10 km of escarpment
= area of impact/15090000 m^2

Hazard = sum of figures in H_r column = 0.00016 per annum

Specific risk = hazard x vulnerability – See Tables 8 and 9.

Probability of road blockage = probability of occurrence of a landslide of volume at least 60 m^3 = 0.00016 per annum (because top entry in column H_r becomes 0.000008 instead of 0.000014).

TABLE 6

Proximal debris flow hazard assessment calculations

Volume (m^3) of entire debris flow	No./year that equal or exceed this volume	Volume range (m^3) of entire debris flow	Mid-point of range on log graph (m^3)	No./year in range, N_r	Area of impact (m^2)	Prob., P_i, of impact, given that event occurs	Prob. of impact per annum $= P_i \times N_r = H_r$
32	0.432	32 – 100	56.2	0.263	14.0	0.000020	0.000005
100	0.169	100 - 320	178	0.102	44.5	0.000062	0.000006
320	0.0667	320 - 1000	562	0.0407	140	0.000196	0.000008
1000	0.0260	1000 – 3200	1780	0.0159	445	0.000623	0.000010
3200	0.0101	3200 – 10000	5620	0.00616	1400	0.00196	0.000012
10000	0.00394	10000 – 32000	17800	0.00242	4450	0.00623	0.000015
32000	0.00152	32000 – 100000	56200	0.000920	14000	0.0196	0.000018
100000	0.000600	100000 – 320000	178000	0.000370	44500	0.0623	0.000023
320000	0.000230	320000 – 1000000	562000	0.000137	140000	0.196	0.000027
1000000	0.000093						

To calculate area of impact, assume a mean thickness of 2 m.
However, assuming that half the volume of the debris flow goes into the proximal part and half into the distal part, divide the mean volume by 4, not 2, to calculate the mean area of impact for each volume range.

P_i = area of impact/area of affected polygons
= area of impact/mean area of (fc + fp + parts of a2, a3, ac, af, and as within the 19° shadow angle) per 10 km of escarpment
= area of impact/714614 m^2

Hazard = sum of figures in H_r column = 0.00012 per annum

Specific risk = hazard x vulnerability – See Tables 8 and 9.

TABLE 7

Distal debris flow hazard assessment calculations

Volume (m^3) of entire debris flow	No./year that equal or exceed this volume	Volume range (m^3) of entire debris flow	Mid-point of range on log graph (m^3)	No./year in range, N_r	Area of impact (m^2)	Prob., P_i, of impact, given that event occurs	Prob. of impact per annum $= P_i \times N_r = H_r$
32	0.432	32 – 100	56.2	0.263	46.8	0.000017	0.000004
100	0.169	100 - 320	178	0.102	148	0.000054	0.000005
320	0.0667	320 - 1000	562	0.0407	468	0.000170	0.000007
1000	0.0260	1000 – 3200	1780	0.0159	1480	0.000536	0.000009
3200	0.0101	3200 – 10000	5620	0.00616	4680	0.00170	0.000010
10000	0.00394	10000 – 32000	17800	0.00242	14800	0.00536	0.000013
32000	0.00152	32000 – 100000	56200	0.000920	46800	0.0170	0.000016
100000	0.000600	100000 – 320000	178000	0.000370	148000	0.0536	0.000020
320000	0.000230	320000 – 1000000	562000	0.000137	468000	0.170	0.000023
1000000	0.000093						

To calculate area of impact, assume a mean thickness of 0.6 m.
However, assuming that half the volume of the debris flow goes into the proximal part and half into the distal part, divide the mean volume by 1.2, not 0.6, to calculate the mean area of impact for each volume range.

P_i = area of impact/area of affected polygons
= area of impact/mean area of (fd + parts of a2, a3, ac, af, as and d2 within 14° shadow angle) per 10 km of escarpment
= area of impact/ 2760000 m^2

Hazard = sum of figures in H_r column = 0.00011 per annum

Specific risk = hazard x vulnerability – See Tables 8 and 9.

TABLE 8

Summary of assessed vulnerability to destruction

Unit	Vulnerability of resident people	Vulnerability of buildings	Vulnerability of roads
b1, b2, b3	0.05	0.25	0.3
fc, fp, and other units susceptible to proximal debris flow	0.9	1	1
fd and other units susceptible to distal debris flow	0.05	0.1	0.3

TABLE 9

Specific annual risk of destruction of people, buildings and roads, and of road blockage. The range of values, taking uncertainties in the recurrence relation into account, is shown in brackets.

Unit	Specific annual risk of death – resident people	Specific annual risk of building destruction	Specific annual risk of road destruction	Specific annual risk of road blockage
Hill slopes	**0.0008%** **1 in 100 000+** (1 in 5 million to 1 in 40 000)	**0.004%** **1 in 20 000** (1 in 1 million to 1 in 8000)	**0.005%** **1 in 20 000** (1 in 1 million to 1 in 8000)	**0.02%** **1 in 6000** (1 in 300 000 to 1 in 2000)
Units susceptible to proximal debris flow	**0.01%** **1 in 9000** (1 in 50 000 to 1 in 2000)	**0.01%** **1 in 8000** (1 in 50 000 to 1 in 1000)	**0.01%** **1 in 8000** (1 in 50 000 to 1 in 1000)	**0.01%** **1 in 10000+** (1 in 60 000 to 1 in 2000)
Units susceptible to distal debris flow	**0.0005%** **1 in 200 000** (1 in 1 million to 1 in 30 000)	**0.001%** **1 in 90 000** (1 in 500 000 to 1 in 20 000)	**0.003%** **1 in 30 000** (1 in 200 000 to 1 in 5000)	**0.007%** **1 in 10 000+** (1 in 60 000 to 1 in 2000)

TABLE 10

Total risk of destruction per polygon per annum

Polygon	Developed area (km^2)	Number of houses and blocks of flats	Estimated number of houses and blocks of flats destroyed per annum	Number of people in houses and flats	Estimated number of resident people killed per annum
Hill slopes					
b1	0.0268	4	0.0002	17	0.0001
b2	2.89	589	0.02	1651	0.01
b3	5.24	2603	0.1	7600	0.06
Proximal part of debris flow					
fc	0.836	228	0.03	639	0.07
fp	0.529	235	0.03	677	0.08
a2(19)	0.173	45	0.006	95	0.01
a3(19)	0.0624	8	0.001	23	0.003
ac(19)	0.000396	-	-	-	-
af(19)	-	-	-	-	-
as(19)	0.0231	3	0.0004	6	0.0006
Distal part of debris flow					
fd	2.41	1042	0.01	3032	0.02
a2(14)	4.03	2224	0.02	6430	0.03
a3(14)	0.240	31	0.0003	69	0.0004
ac(14)	0.0900	15	0.0002	20	0.0001
af(14)	0.377	199	0.002	583	0.003
as(14)	0.107	17	0.0002	29	0.0002
d2(14)	0.00584	1	0.00001	8	0.00004

TABLE 11

Total risk of destruction per km^2 per 100 years

Polygon	Developed area (km^2)	Number of houses and blocks of flats	Estimated number of houses and blocks of flats destroyed per km^2 per 100 years	Number of people in houses and flats	Estimated number of resident people killed per km^2 per 100 years
Hill slopes					
b1	0.0268	4	0.6	17	0.5
b2	2.89	589	0.8	1651	0.5
b3	5.24	2603	2	7600	1
Proximal part of debris flow					
fc	0.836	228	3	639	9
fp	0.529	235	6	677	14
a2(19)	0.173	45	3	95	6
a3(19)	0.0624	8	2	23	4
ac(19)	0.000396	-	-	-	-
af(19)	-	-	-	-	-
as(19)	0.0231	3	2	6	3
Distal part of debris flow					
fd	2.41	1042	0.5	3032	0.7
a2(14)	4.03	2224	0.6	6430	0.9
a3(14)	0.240	31	0.1	69	0.2
ac(14)	0.0900	15	0.2	20	0.1
af(14)	0.377	199	0.6	583	0.8
as(14)	0.107	17	0.2	29	0.2
d2(14)	0.00584	1	0.2	8	0.8

APPENDIX A

Review Comments by Alan Moon
July 1997

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Golder Associates

Celebrating 25 years of Commitment to Engineering Excellence

August 22, 1997

AGSO
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CANBERRA ACT 2601

97661084/3

Attention: Dr Marion Leiba

Re: **REVIEW OF THE PRELIMINARY LANDSLIDE RISK ASSESSMENT FOR THE CAIRNS AREA**

Dear Marion

1. INTRODUCTION

AGSO, with the assistance of Dr Fred Baynes are carrying out a preliminary landslide risk assessment for the Cairns area. AGSO engaged Alan Moon of Golder Associates to carry out an external review of the landslide risk assessment (Golder Associates proposal, July 4, 1997 Reference 97661084/1). At the time of the review a draft report was partially complete and 15 out of 16 draft figures were available. This letter presents the results of the review.

2. SCOPE OF REVIEW

The review included:

- the exchange of ideas, interpretations and judgements associated with critical field observations of the geology and geomorphology;
- the exchange of ideas, interpretations and judgements on the landslide risk assessment process adopted; and
- a review of the partially complete draft report and figures provided.

As the landslide risk assessment is not complete the emphasis was to review the soundness and logic of the approach and study processes rather than presentation details (layout, clarity of expression) and final results. Brief summaries of the report content are included where they help to put the review comments in context.

3. REVIEW COMMENTS

3.1 Scope and aim of study

AGSO have correctly described the preliminary landslide risk assessment as 'an initial regional overview' or 'pilot study'. Considering the scope of the study and the area involved the work to date has been carried out quickly and effectively. In notes produced on site by yourself and Dr Baynes the aims of the study have been described as being:

- map the landslide hazards and produce a quantitative landslide risk map of the Cairns region;
- develop generic techniques for geohazard risk assessment within a GIS environment; and
- provide information to emergency managers and planners to assist in the mitigation of landslide risk.

Within the constraints of a pilot study it is considered that good progress has been made at achieving the above aims.

3.2 Review of previous studies and records of landslides

- The review of previous studies provides a useful background to this study.
- In previous studies landslide probability has been related to slope and underlying rock type. For example, at similar angles, slopes underlain by granite have been assumed to be more likely to fail than slopes underlain by metamorphic rocks.
- Significant landslides including debris flows have occurred since European settlement (record of landslides in Appendix C). The most significant event is a large debris flow at Ellis Beach. A fuller description of the Ellis Beach debris flow including an estimate of the volume should be included in the report. The record of landslides should also include, where possible, description of rock type and where appropriate the data collection process (eg if batter failures, how selected, height, slope etc).

3.3 Field observations

- A reconnaissance geomorphological map on a scale of 1 to 50,000 has been prepared for the study area (about 400 km^2) based on aerial photographs, topographical maps and some site checking. The diary in Appendix A indicates that the map is based on about 7 days field work and about 4 days office work. The reconnaissance nature of the map should be explained on the map.

- Preliminary geomorphological mapping of selected areas on larger scales has also been carried out. On the Redlynch South colluvial fan field mapping was carried out at a scale of 1 to 5000 over a period of about 3 days. This was a worthwhile exercise which allowed time to develop a better understanding of landforms and colluvial deposits.

- The Ellis Beach debris flow and many other landslides and debris flows have been recognised. The draft report indicates that a map of the Ellis Beach area will be included in the draft report.

- At the Redlynch South fan and elsewhere different debris flows can be distinguished by variations in:

  - clast weathering

  - matrix weathering

  - matrix type, consistency or density

  Some debris flows are ferruginised and consist of extremely weathered clasts in a matrix of hard mottled grey and red clay. Fragments of weakly cemented debris material also occur in apparently younger debris flows.

  These observations suggest that debris flows may have occurred over a long period and that some debris flows may be very old.

- The character of debris flow deposits will also depend on the character of the source area of the debris flows. No work has been done in the source area.

- Mapping the characteristics of debris flows, pedology and observations in the source area could help establish relative ages for the debris flows which would help in the assessment of slope process rates and risk. However, in my opinion a lot of work would be required to significantly improve assessment of process rates and such work could be regarded as beyond the scope of this pilot study. Comments about the possible age of debris flows in the draft report should be regarded as speculative at this stage.

- It has been established that debris flows are an important slope process in the study area. The report should define what a debris flow is, include photographs and describe diagnostic features.

- Debris flows (and other landslides) occur throughout the study area in areas underlain by both metamorphic rocks and granite. In light of this study the perception that slopes underlain by granite may have a higher probability of instability than slopes underlain by metamorphic rocks should be reviewed and discussed.

- The sizes of landslides and debris flows should be described quantitatively. On the basis of the field observations it has been assumed that individual landslides on the steeper slopes are 'probably always less than' 10000 m^3. In my opinion larger landslides are possible (for example from the cliffs above Ellis Beach).

3.4 Risk assessment method

- The risk assessment methods and terms appear to be largely consistent with that described in the state of the art paper (SOA 97) from the IUGS (International Union of Geological Sciences) Workshop in Honolulu (Balkema in press). The reason for any variation from the state of the art paper should be explained.

- Reference is made to 'accepted norms' when discussing the 'acceptability of risk'. In my opinion there is no such thing as an 'accepted norm' applicable to landslide risk. Approaches to the consideration of acceptable or tolerable risk for landslides are discussed in SOA 97. For the Cities Project comparison with risks from other natural hazards may be useful.

3.5 Shadow angles

- The concept of shadow angles has been used to assess the potential impact of debris flows on lower slopes. The actual angles have been chosen on the basis of site observations and assumed to be independent of debris volume. The shadow angle concept is reasonable for a pilot study but it ignores the effect of local topography in the transport and deposit area.

- The shadow angles play a critical role in defining areas at risk and should be carefully reviewed before the report is finalised. Studies elsewhere (eg Corominas, Canadian Geotechnical Journal No 33, 1966 pp 260 to 271) suggest that the shadow angles are likely to be dependent on volumes. If, for the purpose of this pilot study the shadow angles are assumed to be independent of volume the potential implications of this simplifying assumption should be assessed and discussed.

- The shadow angles on the draft preliminary maps have been defined by roughly locating ridge tops by hand and then by interactive use of a GIS system. The final maps are difficult to check as they do not show contours. However there seem to have been some errors in the process. The whole process should be checked by hand and the accuracy should be assessed and discussed in the report.

3.6 Process rate assessment

- Initial assessments of process rates on a log volume/log frequency plot (Figure 12) have been made by judgement based on observations, the landslide record and assumptions about a 1 in 10,000 event.

- The assessment of process rates is one of the key components of landslide risk assessment and the concept will need careful explanation in the text, Appendix E and Figure 12.

- The draft Figure 12 has an error on the x scale (one order of magnitude division missing). The x axis legend also needs explanation. The legend refers to number per year whereas the notes in Appendix E indicate that a total failure volume (made up of many landslides) has been plotted. Figure 12 clearly represents a first draft assessment and the process rate evaluation needs a lot more work.

- When considering recurrence intervals from rainfall records it should be recognised that larger landslides are likely to be triggered by longer duration rainfall events.

- Part of one of the assessments is based on observations of road batter failures (from cut slopes). Other assessments are based on landslide and debris flow records. These are different data sets based on different mechanisms and the implication that they are related by plotting them on the same graph with the same symbol is misleading.

- As discussed in Section 3.8 the preliminary risk assessments presented in the draft report show most of the risk to lives, houses and roads results from the low frequency very large events. The concept of maximum credible event should be assessed and discussed.

- The area under the log/log plot represents the shed rate. Geological approaches should be used to assess likely shed rates. For example you could:

  - assess a maximum credible event

  - assess from the reconnaissance mapping the total volume of debris fans

  - plot lines on the log/log plot that pass through the maximum credible event with volumes representing the percentage of the total volume judged to be of Holocene age.

  Similar approaches could be based on judgements on the rate of scarp retreat over a longer period.

  The various approaches should be plotted on the same graph with different symbols to assist the assessment of the rate to adopt for the preliminary risk assessment.

- Although this is a pilot study assessing how the process rate model might be refined helps to understand the limitations/sensitivity of the simple model adopted. One such model would be to distinguish debris flows from other landslides in a way that illustrates how numbers of smaller landslides may coalesce to form a large debris flow.

- In assessing the process rates the 1951 Ellis Beach debris flow is a particularly significant event. The likely frequency of the event should be assessed using geological approaches and discussed in the text. For example the following questions come to mind:

  - how unusual was the 1951 rainfall event (consider different rainfall duration)?

  - was the 1951 rainfall event widespread?

  - did landslides and debris flows occur elsewhere in the study area?

  - what are the implications of the answers to these questions to the judgements of process rates?

A review of rainfall records and the earliest available aerial photographs for selected areas could help answer the above questions.

3.7 Vulnerability, intensity and elements at risk

- Our discussions illustrated how much judgement is involved in assessing the vulnerability and how little guidance there appears to be in the literature. Again they should be checked using other approaches wherever possible. For example, is the estimate consistent with landslide fatality records and judged landslide occurrence in Australia?

- In the preliminary model the vulnerability has been assumed to be independent of debris flow size for the proximal and distal debris flows. Small debris flows may tend to be confined to existing channels and floodways whereas the flow path of larger debris flows may be harder to predict. The implications of this simplification should be considered to help assess the limitations and qualification of this assessment.

- The simplifications used in the assessment of intensity and elements at risk appear reasonable for this pilot study but should be reviewed if any further studies are carried out.

3.8 Preliminary risk assessment results

- As mentioned in Section 3.6 the preliminary risk assessment indicates that most of the risk is associated with the larger events. For example it is assessed that the total annual risk of fatality is 1.22 for the study area and that 40% of that risk is associated with the 1,000,000 to 3,000,000 m^3 events. Larger events have not been considered. In the light of this result it is important to assess what the maximum credible event might be using as many approaches as possible. The use of spreadsheets will enable rapid assessment of the sensitivity of the assessments to different process rates and vulnerabilities.

- The consistency of the assessed annual risk of fatality of 1.22 with the lack of known landslide fatalities in the Cairns area and the Australia wide landslide fatality record should be assessed and discussed.

- The limitations associated with the actual risks presented will need to be carefully explained in the final report. These limitations should be taken into account when comparing landslide risks with risks associated with other natural hazards.

3.9 Draft figures and photographs

- The figures need a lot of work. For example the following should be included on many of the drawings:
  - full titles;
  - description of the nature of the study (preliminary pilot study etc);
  - bar scale;
  - north point;
  - consistent legend;
  - key locations. Every location referred to in the text should be on the drawings.
- It is essential that careful consideration is given about the accuracy of each of the maps and a statement about accuracy included on the map.
- Photographs will be extremely useful and they should be referred to in the main text.

4. OVERALL COMMENTS

Quantitative landslide risk assessments are relatively new developments in geotechnical practice. The accuracy of the predictions made during a landslide risk assessment depend on the extent to which complex natural systems are understood. Excellent progress has been made on the Cairns study in a relatively short time. The study has:

- established that large destructive debris flows have occurred in the study area in modern times.
- developed a conceptual framework for quantifying the risk based on attempting to understand slope processes and slope process rates.

In my opinion the study to date is an impressive piece of work consistent with the current state of the art.

5. DISCUSSION AND FURTHER WORK

- Although this is a pilot study there is a lot of work needed to complete the report. Quantitative risk assessments such as this one involve the complex interaction of many judgements. Finalising the study will involve careful review of each step in the risk assessment processes. Minor changes to one judgement can significantly affect the whole assessment.
- Care will have to be taken to describe the limitations associated with each part of the study. Particular attention will have to be made to explaining the accuracy of the maps and the specific and total risk assessment. Even though it is only a pilot study it is the first quantitative landslide risk assessment for the region and may end up being used for purposes for which it was not intended.

- In the draft report the conclusions and recommendations are in note form only. During preparation of the final report careful thought will have to be given to how the final study aim (third dot point in Section 3.1) can be achieved within the limitations of a pilot study. Communication with the Cairns City Council and possibly local consultants and the public will assist the process.

- The need and benefit for a further external review needs to be considered. Regional landslide risk assessments have the potential to significantly affect land use and peoples' lives and such studies are often subject to external review. The extent of any review (office only or field based) should depend partly on how the Cairns City Council intend to use the results of the pilot study and the likelihood of further work. Further external review is likely to be most effective after the final report including all figures, tables and appendices have been completed and reviewed by both yourself and Dr Baynes.

Yours faithfully
GOLDER ASSOCIATES PTY LTD
per:

Alan Moon
Principal Engineering Geologist
AM/ja
s:\97661084/108403lt

APPENDIX B

Cairns Post **article of 15 January 1951**
on Ellis Beach debris flows

HUGE LANDSLIDES ON PART OF COOK HIGHWAY

REPAIR WORK WILL COST MANY THOUSANDS

It will cost the Main Roads Commission many thousands of pounds to repair a six-mile stretch of the Cook Highway between Buchan and Simpson's Points, following huge landslides caused by a torrential downpour lasting nearly five hours.

Almost unbelievable quantities of earth and debris were swept from the mountain-side down on to the roadway and over the precipice into the sea. Gigantic trees were uprooted and ground to pulp, and boulders as high as 10 feet hurled into the Pacific as if they were marbles.

Millions of gallons of water cascaded down the mountains into the sea, gouging huge ravines and making swiftly running streams in the thousands of tons of earth and rubble left on the road in the wake of the slides.

Repair work was begun on Saturday by gangs sent out by the Main Roads Commission and the Douglas Shire Council. Officials said last night that essential users of the Cook Highway would be assisted by man-power and tractors from about 10 a.m. to-day.

ROAD REPAIR GANGS AT WORK

A spokesman for the Main Roads Commission claimed that repair work would occupy many weeks, and would cost the State Government thousands of pounds. It would be at least a fortnight, he said, before the six-mile stretch could carry normal traffic.

Road repair gangs worked in all daylight hours during the week-end. Commission men from the Buchan's Point end and shire workmen from Simpson's Point. They used heavy graders, tractors and bulldozers in an effort to shift huge tonnages of earth and clear waterways.

The two bodies, working toward each other, hope to meet early this morning. When they do, essential users of the road will be assisted on their journey. Vehicles will need "nursing" over potholes and dangerous sections.

R.A.C.Q. WARNING.

The secretary of the Cairns branch of the R.A.C.Q. (Mr. R. H. Crust) said last night that heavily-laden trucks should not attempt the highway at this stage; neither should private motorists. The road was closed to all but essential users, he said

TWO AND A HALF FEET OF RAIN.

The torrential deluge that precipitated the landslides yielded between 25 and 30 inches of rain in just under five hours.

The slides were small at first, but gradually became bigger as the rain continued. Those causing the heaviest damage were as long as 80 yards and 60 to 75 feet high.

At the height of the slides millions of gallons of water raced across the road from the mountains along the bottom of which the highway is built, in some parts almost at sea level.

AMAZING SCENE.

[illegible]

"POCKET TORNADO'S" DESTRUCTION

FARMHOUSE BLOWN DOWN

IN MACKAY DISTRICT.

MACKAY, Jan. 14.—As miles of damaged trunk lines are being restored in the district, news reached Mackay at the week-end of a fierce pocket tornado, in which five persons had narrow escapes from death at the Habana settlement, 12 miles from Mackay.

They were occupants of a five-roomed farmhouse which they quit 30 seconds before it was blown to matchwood before their terrified gaze.

The escapees were farm owners, Messrs. H. and G. H. Brown, of Neville road, Habana, and Vic and Arthur Brown, sons of Mr. H. Brown, and an eight-years-old boy, Ronald Cowan.

According to eyewitnesses and the party who got through to the devastated farm to-day, the Browns were breakfasting about 7 a.m. on Thursday when they heard what sounded like a plane about to crash.

Terror-stricken, they rushed outside, and within 30 seconds the farm house, constructed of timber, was smashed to matchwood and littered in a radius of 50 yards from the stumps on which it had been standing. A dog and poultry which rushed under the house for shelter were crushed to death.

Sheets of iron from the farmhouse were found up to two miles away, although a windmill and a tank only 50 yards from the home site were untouched. The tornado was confined to a narrow belt of destruction about 15 chains wide. Whole trees were snapped off and [illegible] their position. Reports reaching [illegible]

SITE FOR NEW TOWN

IN PETRIE AREA

HOUSING COMMISSION'S PLAN

BRISBANE, Jan. 14.—The Queensland Housing Commission plans to make the Petrie area, about 20 miles from Brisbane, the site of a big town of 300 homes within five years, with a water supply, a £1 million paper mill, and an electric train service to Brisbane.

The houses are to be built at Lawnton and Strathpine, the first 1000 during the next 2½ years and the remainder during the next 2½ years.

The paper mill is being established by Australian Paper Manufacturers Ltd., and the electric trains are part of the State Government's plan for the electrification of suburban railway lines.

The mill is now in the planning stage, but during this year mill machinery worth £250,000, representing the bulk of the plant, will arrive in Australia from England, said Mr. Feinaigle, project manager of Australian Paper Manufacturers Ltd., to-day. Major mill construction work is expected to begin in 1952. The Pine Shire's water supply scheme would have to be altered because of the big housing development, Mr. Feinaigle said. Originally the Pine Shire Council had agreed to help the paper project by constructing a weir across the North Pine River to also serve as a water supply for Petrie township.

VICTIM OF STABBING

LEFT AT HOSPITAL

MELBOURNE WOMAN CHARGED

MELBOURNE, Jan. 14.—A [illegible]

Cease-fire Pl[illegible] Before U.N.

Principles Approv[ed]

NEW YORK (A.A.P.).—The United [illegible] Political Committee to-day approved the principles [illegible] five-point cease-fire plan [illegible] viding for a conference [illegible] Far Eastern problems [illegible] as the fighting in Korea [illegible] ended.

Russia voted [illegible] This caused immediate specul[ation] that the Chinese Communis[t] gime would reject the plan. [Vot]ing was 50 to seven, with Philippines abstaining. Ne[gative] votes were cast by the five S[oviet] bloc countries, Nationalist C[hina] and El Salvador.

The Soviet delegate (Mr. Malik) said he voted agains[t] cease-fire principles because [nei]ther the North Korean Go[vern]ment nor Communist China [was] present.

Dr. T. Tsiang, of Natio[nalist] China, told the committee the cease-fire plan was a "sell-out on the United Na[tions] Korea and China."

The Philippines Foreign [Min]ister (Carlos Romulo) charge[d] United Nations that it wou[ld be] surrendering to intimidation [and] blackmail if it agreed to c[onfer] with Peking on the futur[e of] Formosa and on the repres[enta]tion of China in the United [Na]tions in return for a truc[e in] Korea.

After a long procedural d[ebate] the committee decided to as[k] Secretary-General (Mr. T[rygve] Lie) to send the five-point [plan] to Peking with a request f[or a] reply as soon as possible.

The committee adjourned [with]out fixing a date for its [next] meeting.

PRIME MINISTERS CONFERENCE

TEN-DAY TALKS EN[D]

BID FOR PEACE OUTLIN[ED]

LONDON, Jan. 13 (A.A.P.-[Reu]ter's). — British Commonw[ealth] Prime Ministers announced a[t the] end of their 10-day conferen[ce in] London to-day that they "do [not] seek to intervene in the affai[rs of] the Soviet Union, China or [any] other country."

"We are simply determined t[o ob]tain mastery of our own a[ffairs] without fear of aggression," [they] declared in a long formal state[ment].

The Prime Ministers annou[nced] they would "welcome any fr[ank] arrangement for a frank exch[ange] of views with Stalin and Mao [Tse-]tung."

WANT CO-OPERATION.

The statement [illegible] the conference [illegible] toward securing [illegible] tilities in Korea [illegible] monwealth countries welcomed co-operation [illegible] "We will [illegible] by cussion to promote [illegible] among ourselves [illegible] common international [illegible] the United States [illegible] friendly co-operation [illegible] statement added. [illegible]

RETAIL [illegible]

Cairns Post
15 January 1951

Cairns Post
15 January 1951

[illegible] ... were as long as [illegible] yards [illegible] 75 feet high.

[illegible] of the slides millions of gallons of water raced across the road from the mountains, along the bottom of which the highway is built, in some parts almost at sea level.

AMAZING SCENE.

The scene the repair gangs were met with was described by one workman as "nothing sort of amazing." Hefty slabs of bitumen were tilted up from the road; there were massive boulders everywhere; earth and mountain debris was piled up as high as 10 feet; water flowed in swift currents across the roadway, swirling round trees lopped of their branches, and huge rocks.

All culverts and inverts between Buchan and Simpson's Points have either been damaged considerably or washed away entirely.

The sea shore was described by a Main Roads official last night as being "very much like a huge wall of seaweed."

Boulders "as big as motor cars" and the huge falls of earth have created a bank-like structure which, in places, stands as high as 10 and 15 feet.

He said that further minor damage was caused between Simpson's and Yules' Point. This, however, could be repaired within a very short space of time.

VEHICLES HELD UP.

Passengers in a tourist coach bound for Mossman on Friday afternoon had to leave the coach and walk back to Buchan's Point. The heavy train made driving too hazardous, especially as minor slides were beginning. The coach, with several private cars, was left overnight at various points between Buchan's and Simpson's points.

STORMS AT CAIRNS.

Cairns had several very heavy downpours of rain during the week-end, including two on Saturday night and one about 6.15 p.m. yesterday. The latter fall lasted about three-quarters of an hour, during which time 238 points were registered.

Last night's fall was the heaviest for some time, and it was only a few minutes before the city streets carried huge sheets of water and the gutters temporarily flooded.

Cars returning from the beaches had to be driven through sheets of water on the roadway at Stratford, and at Aeroglen a long line of vehicles was forced to travel at snail's pace through the water. Cars with very low clearance were forced to wait until the water receded before they could continue their journey.

Sandbags were placed in the doorways of some city stores when gutters seemed likely to overflow.

COLLINS BRIDGE FLOODED.

KURANDA, Jan. 14.—Road traffic on the Cairns-Mareeba highway was disrupted on Saturday for about 14 hours. Flood waters from the Barron River rose above the road level of the Collins bridge at Kuranda early on Saturday morning, and it was about 9 o'clock at night before the first vehicle was able to get across. At this time there was still about two feet of water flowing over the bridge. To-night the water was about six inches below road level, but with further heavy thunderstorms sweeping the district to-night, there may be a further rise in the river to-morrow.

Several floats with nine horses for the Cairns Jockey Club's race meeting at Cannon Park arrived at Kuranda on Saturday morning, but as the Collins bridge was then submerged by the flood waters, the horses were taken back to Mareeba.

[illegible] ... about to crash.

Terror-stricken, they rushed outside and within 30 seconds the farm house, constructed of timber, was smashed to matchwood and littered in a radius of 50 yards from the stumps on which it had been standing. A dog and poultry which rushed under the house for shelter were crushed to death.

Sheets of iron from the farmhouse were found up to two miles away, although a windmill and a tank only 50 yards from the home site were untouched. The tornado was confined to a narrow belt of destruction about 15 chains wide. Whole trees were snapped off and fences blown away yards from their position. Reports reaching the city at the week-end indicated that there were at least six other "pocket tornadoes" about the same time in widely separated areas. In all cases, however, only minor damage was recorded.

FURTHER HEAVY RAIN

EXPECTED IN THE NORTH

WEATHER BUREAU REPORT.

BRISBANE, Jan. 14.—The Weather Bureau reported to-night that the inland rain depression had moved west to north-west to the north-west border area of the State and rains had eased over all flooded areas except on the Far North tropical coast and lower Carpentaria where local heavy falls were expected.

From recent rains in the central interior, strong stream rises were extending downstream to the south-western parts of the State, but over these districts finer weather with only local thunderstorm activity was now likely. The south-easterly change associated with the movement of the southern high pressure system centred over Tasmania had advanced into the south-west border areas.

Scattered showers and local storms along the southern border areas were expected as this change extended north-east to the south coast. In the past 24 hours fairly general rain was reported on the tropical coast and Carpentaria with a few over inch amounts. Scattered light falls were reported in the western districts. Heaviest falls were 292 points at Karumba and 228 points at Cairns.

[illegible] ... water supply [illegible] to be altered [illegible] housing development [illegible] said. Originally [illegible] Shire Council had agreed [illegible] the paper project by constructing a weir across the North Pine River to also serve as a water supply for Petrie township.

VICTIM OF STABBING

LEFT AT HOSPITAL

MELBOURNE WOMAN CHARGED.

MELBOURNE, Jan. 14.—A victim of a stabbing affray was left at the casualty entrance of Prince Henry's Hospital yesterday by an unknown man in a car. The driver of a car left the man at the hospital and drove away without leaving his name or disclosing where he had found him.

Homicide detectives later searched through Government records of men employed on the Melbourne waterfront and discovered that the wounded man's name was Maurice Maxwell Francis (28), painter and docker, of South Melbourne. He was operated on and his spleen removed. His condition is satisfactory.

Police allege that soon after 5.30 p.m. yesterday Francis was stabbed with a bread knife after a quarrel with a woman. Later at the City Watchhouse a 29-year-old woman was charged with intent to murder.

SALVAGE OF PALANA

EXPERT CONFIDENT.

BRISBANE, Jan. 14.—The Brisbane salvage expert, Captain J. W. Herd, is confident that the holed P. and O. freighter, Palana, can be salvaged. Captain Herd said that salvage would begin when all the equipment now delayed by the floods arrived. Previous salvage attempts had to be abandoned when the wreck was battered by cyclonic storms.

Shipping experts in Brisbane said to-night that the Palana would probably be beached near Mackay, where temporary repairs can be made. The Palana would probably then be towed to Brisbane, a job which would take four or five days. The tug, Coringa, which set out from Brisbane on Saturday morning with pumps and a powerful tow rope, is expected to reach the Palana to-morrow.

BOXING

HASSEN v BAILEY

SYDNEY, Jan. 14.—The Australian lightweight champion, Jack Hassen, is expected to concede six lb to the heaviest opponent of his career when he meets Ken Bailey at Sydney Stadium to-morrow night. Hassen weighed 10.0¾ after a rub down to-day. He will probably weigh in at 10 stone.

Bailey to-day scaled 10.8 and may be 10.6 at to-morrow afternoon's weigh in.

[illegible] ... whatever sacrifices [illegible] hold [illegible] principle [illegible] order, which [illegible] for world peace [illegible]

RETAIL LIQUOR TRADE

"RUSH" DRINKI[NG] CONDEMNED

BRISBANE, Jan. 14.—Th[e] liquor trade in Queenslan[d] be reformed, Dr. J. V. Du[hig] leading liquor reformist, sa[id] night.

He was commenting on [a state]ment by Archbishop Duh[ig] which he condemned "rush[ing]" and "gorging," and [...] the licensing of grocers [...] men could take their liquor and drink it at meals. [...] could be shown that th[e licens]ing of grocers would resul[t in im]proved drinking conditio[ns] would be in favour of it," sa[id] Duhig. "I have always b[een op]posed to the system of b[...] the bar three and more dee[p] sinking pints just for the s[ake of] drinking. The whole t[hing is] barbarous and has resulte[d in] greatly increased consumpti[on of] beer a head in population," [said] Dr. Duhig.

CHILD KILLED [IN] FALL

STARTED FATHE[R'S] TRUCK.

SYDNEY, Jan. 14.—A t[...] old boy who apparently [...] into his father's unattended truck in Petersham to-day a[nd re]leased the handbrake, was [killed] when he was thrown to the way.

He was David John Ma[...] Che[s]ter-street, Petersham [...] truck was parked outside [his] home. It is believed he fe[ll] after it had travelled ab[out ...] yards.

MOTOR CYCLI[ST] SMASH

LEG AMPUTATE[D IN] HOSPITAL

BUNDABERG [illegible] neth John Dun[...] (39) [...] ployed at Gin Gin [illegible] riding his motor cycle [illegible] Gin on Saturday [illegible] came into collision [illegible] car travelling [illegible] direction [illegible] tance [illegible] ceived [illegible] right [illegible] tated [illegible] His condition [illegible]

APPENDIX C

CAIRNS AREA

LANDSLIDE DATABASE

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June 1997

CONTENTS

INTRODUCTION

This landslide database was compiled in early 1997 as a resource for the Australian Geological Survey Organisation (AGSO) Cities Project landslide risk assessment of Cairns.

We are very grateful to the Cairns City Council and Queensland State Emergency Service for their assistance with both transport and observations in the field.

The Cairns Historical Society provided much information on earlier landslides. Their information was invaluable in compiling the landslides master list, and we are most grateful for their help. We are also grateful to Graham Haussmann for his information about early events.

CAIRNS LANDSLIDES - MASTER LIST

The reference number is that in the GIS

1. 8 March 1878: Flood followed by severe cyclone triggered many landslides across the inlet. They could be heard distinctly in Cairns (Jones, D., 1976, p. 125).

1891: During the construction of the Cairns railway, a heavy landslide occurred during an early, heavy and prolonged wet season (Ellis, R.F., 1976).

16 April 1894: 965 mm of rain fell during the month. The railway was blocked by 20 landslides and numerous washouts (Broughton, 1984).

2./3. 1896: Following a prolonged wet season, large landslides blocked the line at the Springs between No. 14 tunnel and Red Bluff, and at No. 15 tunnel (Broughton, 1984).

1897-1906: Minor rock falls occurred on the Cairns railway (Broughton, 1984).

31 May 1900: Five men were killed and one buried alive for one and a half hours when a 7.6 m (25 ft)-deep tramway cutting they were constructing in alluvial sandy loam, clay and gravel in a river terrace at Riverstone for the Mulgrave Central Mill caved in (Morton, 1995; *Morning Post*, Cairns,N.Q., 1, 8 &15 June 1900). The locality is now known as "Dead man's Gully" or Dead man's Cutting" (A. Broughton, Cairns Historical Society, written communication, 1999) and is situated 3 km WNW of Walshs Pyramid in Gordonvale.

5. 1910: There was a landslide on the Cairns railway at Surprise Creek (Broughton, 1984).

4. 15 December 1910: Landslide at Kuranda end of No. 10 tunnel on Cairns railway partly closed the tunnel for more than two months. Several episodes of sliding occurred during this time (Broughton, 1984). The line was cleared for goods traffic on 25 February 1911, and for all traffic on 6 March 1911 (*Cairns Post*, 27 February and 7 March 1911).

Early January 1911: A Cairns Post reporter noted that there had been small landslides at various places, but that the obstructions had been removed. The most serious fall was at the 15 mile, but that it would be cleared quickly. Lower down the line, one or two trivial falls had also been cleared (*Cairns Post*, 4 January 1911).

Early January 1911: There were rumours of a big washaway at 3.5 miles from Cairns near Edge Hill quarry, which would be repaired in a few hours (*Cairns Post*, 4 January 1911).

6. 7 February 1911: There was a big fall on the railway at 17.75 mile near Surprise Creek (Broughton, 1984).

Ca. 13 February 1911: A landslide blocked the tramway on the Aloomba side of the Mulgrave River. It was expected to be cleared on 15 February 1911 (*Cairns Post*, 15 February 1911).

8. 3 March - 2 April 1911: A failure under the railway line between No. 11 and No. 12 tunnels was caused by heavy rain (Broughton, 1984).

4. 16 March 1911 cyclone: At No. 10 tunnel, earth and boulders from overhead fell and blocked the railway line (*Cairns Post*, 18 March 1911).

7/5.16 March 1911 cyclone: Falls occurred on the railway line near Stony Creek bridge and at Surprise Creek (Broughton, 1984).

7. 16 March 1911 cyclone: There was a fall at 14.25 miles which temporarily blocked the line (*Cairns Post*, 18 March 1911).

6. 16 March 1911 cyclone: There was another subsidence at 17 miles 50 chains (*Cairns Post*, 18 March 1911).

9. 1 April 1911: A big landslide occurred in the Nisbet Ranges across the inlet from Cairns. The scar could be seen in photos for several years afterwards (A. Broughton, Cairns Historical Society, personal communication, 1997). The landslide brought away trees, rocks and everything else from a considerable distance up the mountain side (*Cairns Post*, 3 April 1911).

10. 31 March - 2 April 1911: On the railway at Horseshoe Bend, south of Redlynch, the formation was washed out (Broughton, 1984).

11. 31 March - 2 April 1911: Landslides covered the line near No. 6 tunnel (Broughton, 1984).

12. 31 March - 2 April 1911: On the railway, from Stony Creek to the Springs, there were washouts and the undermining of the embankment (Broughton, 1984).

13. 31 March - 2 April 1911: From the Springs to Red Bluff, two big landslides of about 1000 tons had blocked the line for a considerable distance (Broughton, 1984).

3. 31 March - 2 April 1911: On the Kuranda side of No. 15 tunnel, there was a large fall (Broughton, 1984).

14. 31 March - 2 April 1911: Further along, the railway line was badly undermined and scouring had left the line hanging (Broughton, 1984).

5. 31 March - 2 April 1911: Near Surprise Creek, 1500 tons of mud and rock covered the line for five chains (Broughton, 1984).

15. 31 March - 2 April 1911: Just up the line was another fall of 500 tons (Broughton, 1984).

16. 31 March-2 April 1911: At Mervyn Creek, the line was covered to a depth of 4-6 m by another large landslide (Broughton, 1984).

1912: More landslides occurred on the Cairns railway (Broughton, 1984).

30 January 1913 cyclone: There was a landslide on the range between Kuranda and Cairns (*Cairns Post*, 1 February 1913).

17. 9 February 1927 cyclone: In upper Freshwater Creek, east of Jigol Creek, boulders pounded the concrete, in which new pipes had been set, to pieces and carried away the pipes (Cairns City Council, 1927).

18. 9 February 1927 cyclone: A portion of Chirio's farm was washed away (this may have happened on 12 February) (Cairns City Council, 1927).

19. 9 February 1927 cyclone: At Freshwater Creek, about 1 km WSW of Brinsmead, a pipe was broken near a washout about 1 km long (Cairns City Council, 1927). The creek here alters course (G. Haussmann, retired City Engineer, personal communication, 1997).

19A. 1932: The construction of the original above-ground hydro-electric power station at the bottom of the Barron Falls was abandoned because of major rock falls and other complications (Jones, D., 1976, p. 460).

March 1934 cyclone: At Slip Cliff Point on the Captain Cook Highway, about 200 000 tons of rock crashed down across the road, closing it. The road was relocated to a higher alignment. There are claims that the sound was heard in Port Douglas and Cairns (Richards, 1996).

19B. 1939: There were several landslides in new cuttings in Redlynch Intake Road near the last crossing on Freshwater Creek (Mulgrave Shire Council, 1969).

20. 12 January 1951: A torrential deluge of about 700 mm of rain in just under five hours, triggered debris flows over 10 km of the Captain Cook Highway between Buchan and Simpson's Points. Huge quantities of debris were swept from the mountainside on to the road and over the precipice into the sea. Boulders up to 3 m long were hurled into the Pacific like marbles. Large slabs of bitumen were tilted up from the road, and landslide debris was piled as high as 3 m. All culverts and inverts in this area were either damaged considerably or washed away entirely. The highway was not expected to carry normal traffic for at least two weeks (*Cairns Post*, 15 January 1951).

21. 5 March 1954: A large landslide in the Red Bluff area, with its head well above the railway and the toe well below it, blocked the Cairns railway from 5 March until 22 April 1954 (A. Broughton, Cairns Historical Society, personal communication, 1997).

21B. 1967: 300 000 m^3 of the hillside slipped down on to the road going to the base of the quarry face at White Rock. The quarry was closed temporarily (Don Healy, personal communication).

21A. 10 March 1970: Following about two weeks of rain at 25 mm a day, then about 200 mm of rain in two hours on 10 March, about 50 landslides occurred on hills in Whitfield - Edge Hill and other areas to the west of Cairns CBD. Part of Whitfield was the worst affected. A slide 50 m long, almost liquid, went under a house and on to the road in front of it. There were phone calls from residents with landslides pushing against their houses in various parts of Cairns (G. Haussmann, personal communication, 1997).

22. 1979: Following very heavy rain, a 60 m x 60 m batter and fill failure on Lake Morris Drive behind Earlville/Bayview Heights took out a section of road which was then closed for about six months. This section of road was 50% damaged again in 1981, and the road was nearly abandoned (G. Haussmann, personal communication, 1997).

23. Around 1979: A landslide near the reservoir tanks on the south side of Brinsmead-Kamerunga Road blocked the road (Member of Cairns Historical Society, personal communication, 1997).

21A. Around 1979: In Whitfield, a hill slope failed and went straight through houses. Mud went into the back of one house (Member of Cairns Historical Society, personal communication, 1997). Is this the event of 10 March 1970?

24. Around the 1980s: Mud went straight through a newly completed house in Smithfield Heights. The house was not structurally damaged (*Cairns Post* employee, personal communication, 1997).

24A. 1984 or 1985: Boulders smashed the water main at No. 3 crossing on Freshwater Creek and, either before or after that, the main slipped with a mudflow which took out the anchor blocks (D'Arcy Gallop, Cairns City Council, personal communication, 1997).

25. 1988: A landslide in Bayview Heights wrote off two or three building blocks.

26. 1990 or earlier: A fill failure on the NW side of Granadilla Drive, Earlville caused one lane to be closed permanently.

27. 23 December 1990 Cyclone Joy: Undercutting by a creek caused a landslide on the south side of Granadilla Drive/Comet Street, Earlville/Bayview Heights which closed this section of road permanently - only a walkway remains.

28. ?1990s: There have been slope stability problems in part of Mooroobool (Two different citizens of Cairns, personal communication, 1997).

29. ?1990s: A landslide caused a small part of Kamerunga to be permanently abandoned. The roadway and stormwater drains were broken.

30. 1990s: A house in Bayview Heights has a slump in talus in the excavation at the back.

31. ?1990s: In Mooroobool, a house was destroyed due to batter failure at the rear, and rebuilt.

32. ?1990s: In Earlville a partly completed house was written off due to 300 mm of movement.

October 1995: A landslide in the Kuranda Range closed the Cairns railway for several days (Linda Berry, James Cook University, personal communication, 1997).

33. 1997: A debris slide about 3 m high by 2 m wide occurred in the batter on the north side of the Brinsmead-Kamerunga Road.

34. 1997: Small batter failures occurred on the hillslope to the east of Brinsmead.

36. 1997: Recent failure in weathered rock in rainforested area in Barron Gorge, estimated 20 m high x 2m wide, on opposite side of gorge to railway line.

37. 1997: Near Barron River Falls Railway Station, there are three batter failures in red, highly weathered rock. Two are 2-3 m high x 2 m wide and one is 2-3 m high x 1 m wide.

1997: In Freshwater Valley, on the Cairns Railway, there is a small batter failure about 0.7 m high x 2 m wide in weathered rock.

13. 1997: On the south side of Red Bluff, debris frequently falls, including in 1997 (Linda Berry, James Cook University, personal communication, 1997).

1997: Small batter failures occurred during this wet season along Lake Morris Drive.

23 March 1997, T.C. Justin: Numerous batter failures occurred along Lake Morris Drive, and the Kuranda Range Road. Batter failures were also logged along the Cairns Railway, Toogood Road, Redlynch Intake Road, Yarrabah Road, Reservoir Road, and in Rainforest Estate.

96J. 23 March 1997, T.C. Justin: A landslide about 600m long and 15 m wide occurred on a natural slope on the escarpment 8.5 km west of Gordonvale.

FAILURES LOGGED ALONG LAKE MORRIS DRIVE ON 5 MARCH 1997

The reference number is that in the GIS

Dimensions of failures are given as width x height in metres

Odometer starting at dam gate 987.7 km

35. Old fill failure 25m long x ½ carriage way

35. Old fill failure 10m long x ½ carriage way

35. New local shallow batter failure 10 x 10m (10 - 100m^3)

35. New 3 x 1m batter failure (vol ~0. 1m^3) 988.2 km

35. New 3 x 1m batter failure (vol ~0. 1m^3)

35. Two old 25m long fill failures x ½ carriage way

35. New batter failure 3 x 1m (vol <1m^3) 990.3 km

35. New batter failure 3 x 1m (vol <1m^3)

35. New fill failure at edge ~ 15m long 990.9 km

35. New batter failure 1 x 6m (vol ~1m^3)

35. New batter failure 2 x 4m (vol <1m^3)

35. New batter failure 3 x 3m (vol ~1m^3) 991.8 km

35. Old 10m long fill failure

35. New batter failure 1 x 3m (vol <1m^3)

35. New batter failure 0.7 x 2m (vol $<<$1m^3)

Top of scarp 993.5 km

35., Old fill failure 5m long

35. Rock fall debris ~3m^3 of debris 993.9 km

35. New 1m x 5m batter failure (vol <1m^3)

35. New reactivated 10 x 5m rock fall (vol 1-2m^3)

22.	Several old rock falls in last 10 years (vol ~10m^3)	994.7 km
35.	New batter failure ~1 x 10m (vol <1m^3)	
35.	2 new batter failures (vol ~1m^3 altogether)	995.2 km
35.	New batter failure ~2 x 6m (vol <1m^3)	
35.	New batter failure ~1 x 3m (vol <1m^3)	
35.	New fill failure 5m long and clipped edge of road	
35.	New batter failure 5 x 8m ($\geq$10m^3)	997.4 km
35.	New batter failure - rock fall (vol ~1m^3)	
35.	Old fill failure ~10m long	
35.	Old ~10m long fill failure	
35.	New ~2 x 3m batter failure (vol <1m^3)	
35.	New batter failure 4 x 10m (vol ~2m^3)	000.3 km

End of road 002.2 km

Road section length 14.5 km

FAILURES TRIGGERED BY RAIN FROM TROPICAL CYCLONE JUSTIN
The reference number is that in the GIS

Dimensions of failures are given as height x width in metres

Failures along Lake Morris Drive logged on 9 April 1997
Odometer reading at lower dam gate 0.0 km
Odometer reading at upper dam gate 0.8 km

32J. Very small batter failure 0.5 x 0.5m (vol <<$1m^3$)	1.3 km
33J. Batter failure 2 x 1m (vol <$1m^3$)	3.1 km
34J. Batter failure 2 x 1.5m (vol <$1m^3$)	4.5 km
34J. Batter failure 2 x 6m (vol <$1m^3$)	4.6 km
35J. Batter failure 2 x 1m (vol <$1m^3$)	4.9 km
36J. Batter failure 2 x 1m (vol <$1m^3$)	5.1 km
36J. Batter failure 2 x 1m (vol <$1m^3$)	5.2 km
37J. Batter failure 1 x 1m (vol <$1m^3$)	5.3 km
37J. Two batter failures, each 2 x 1m (vol <$1m^3$)	5.3 km
37J. Batter failure 2 x 2m (vol <$1m^3$)	5.4 km
38J. Batter failure 2 x 1m (vol <$1m^3$)	5.9 km
39J. Batter failure 1 x 0.5m (vol <$1m^3$)	6.2 km
39J. Batter failure 2 x 0.5m (vol <$1m^3$)	6.2 km
39J. Batter failure 6 x 6m (vol ~$8m^3$)	6.3 km
40J. Batter failure 2 x 1m (vol <$1m^3$)	6.6 km
40J. Rock fall (vol ~ $0.5m^3$)	6.6 km
40J. Batter failure 4 x 2m (vol ~$1m^3$)	6.7 km
40J. Batter failure 6 x 4m (vol ~$3m^3$)	6.75 km
41J. Batter failure, debris slide 15 x 15m (vol ~$8m^3$)	6.8 km
41J. Batter failure 5 x 1m (vol ~$1m^3$)	6.85 km
42J. Rock fall (vol ~$1m^3$) (Is it new?)	7.0 km

43J. Rock fall (vol ~1m^3)	7.2 km
43J. Batter failure 1 x 1m (vol <1m^3)	7.25 km
43J. Batter failure 2 x 1m (vol <1m^3)	7.3 km
43J. Reactivated batter failure 2 x 1m (vol ~1m^3)	7.35 km
44J. Very big reactivated old landslide (originally 1950s, then 1979, then 1980, then 1985) (volume several m^3)	7.5 km
45J. Batter failure 5 x 2m (vol 1-2m^3)	8.3 km
45J. Batter failure 6 x 1m (vol ~1m^3)	8.4 km
45J. Batter failure 1 x 3m (vol <1m^3)	8.45 km
46J. Batter failure 2 x 1m (vol ~1m^3)	8.7 km
46J. Batter failure 6 x 1m (vol ~1m^3)	8.75 km
47J. Corner slide - batter failure (vol 1-2m^3)	9.1 km
47J. Batter failure 3 x 1.5m (vol ~1m^3)	9.15 km
48J. Batter failure 5 x 3m (vol 5-6m^3)	9.4 km
48J. Batter failure 3 x 3m (vol ~3m^3)	9.5 km
49J. Batter failure 10 x 1m (vol ~1m^3)	10.05 km
50J. Batter failure 15 x 2m (vol ~3m^3)	10.3 km
50J. Batter failure 10 x 5m (vol ~10m^3)	10.4 km
51J. Batter failure, very small rock fall 1 x 1m (vol <<1m^3)	11.2 km
52J. Batter failure 3 x 2m (vol ~1m^3)	11.5 km
53J. Batter failure 5 x 0.5m (vol ~0.5m^3)	11.9 km
53J. Batter failure 2 x 1m (vol <1m^3)	11.9 km
54J. Batter failure 3 x 0.5m (vol <1m^3)	12.8 km
54J. Batter failure 2 x 0.5m (vol <1m^3)	12.9 km
55J. Reactivated big batter failure 15 x 4m (vol ~1m^3)	13.4 km
56J. Batter failure 4 x 4m (vol ~1m^3)	13.55 km

56J. Batter failure 2 x 1m (vol <1m^3) 13.6 km

57J. Batter failure 2 x 0.5m (vol <1m^3) 13.9 km

58J. Batter failure, anthill fall 1 x 0.5m (vol <1m^3) 14.6 km

59J. Batter failure 3 x 1m (vol <1m^3) 14.9 km

59J. Batter failure, anthill fall (vol <1m^3) 15.0 km

End of road 15.3 km

31J. **Reservoir Road, south side**
Small batter failure 1 x 2m (vol ~0.5m^3) 16.2 km

Failures along Kuranda Range Road logged on 9 April 1997
Starting from the Smithfield end
Odometer reading at start of road 0.0 km

1J. Small rock fall (vol~0.5m^3) 1.7 km

2J. Batter failure 2 x 1m 2.1 km

2J. Batter failure 4 x 0.3m 2.1 km

3J. Batter failure 1 x1m 2.4 km

4J. Batter failure 3 x1m 2.6 km

5J. Batter failure 10 x2m 3.5 km
(visible from Smithfield shopping centre)

5J. Batter failure 3 x1m 3.5 km

6J. Batter failure 2 x3m 4.0 km

6J. Batter failure 2 x3m 4.0 km

7J. Batter failure 2 x1m 4.15 km

7J. Batter failure 4.2 km

8J. 15m long fill failure right at edge of road 5.0 km

9J. Batter failure 3 x2m 5.25 km

9J. Batter failure 2 x1m 5.25-5.45 km

9J.	Batter failure 5 x1m	5.25-5.45 km
9J.	Batter failure 1 x10m	5.25-5.45 km
10J.	Batter failure 10 x2m	5.4 km
10J.	Batter failure 15 x2m	5.4 km
11J.	Batter failure 5 x2m	5.6 km
12J.	Batter failure 2 x1m	5.8 km
13J.	Batter failure 3 x2m	6.0 km
13J.	Batter failure 1 x1m	6.0 km
14J.	Batter failure 3 x1m	6.2 km
14J.	Batter failure 10 x2m	6.3 km
15J.	Batter failure 2 x2m	6.4 km
15J.	Batter failure rock fall 2 x2m	6.55 km
16J.	Two small batter failures	6.8 km
17J.	Batter failure 10 x10m (vol ~$2m^3$)	6.9 km
17J.	Two small batter failures	6.95 km
18J.	Batter failure 2 x 2m	7.3 km
18J.	Batter failure 5 x 0.5m	7.35 km
19J.	Batter failure	7.5 km
19J.	Batter failure 2 x 1m	7.6 km
19J.	Batter failure 1 x 1m	7.6 km
19J.	Batter failure 2 x 1m	7.7 km
20J.	Batter failure 2 x 5m	8.4 km
20J.	Batter failure 5 x 5m	8.5 km
21J.	Small vol ~100m batter failure	8.75 km
22J.	Batter failure 2 x 2m	9.2 km
23J.	Batter failure 2 x 1m	9.5 km

24J.	Batter failure 3 x 15m	10.3 km
24J.	Batter failure 2 x 0.5m	10.3 km
24J.	Batter failure 0.5 x 0.5m	10.3 km
25J.	Batter failure 3 x 2m	10.5 km
26J.	Batter failure 3 x 4m	10.75 km
27J.	Batter failure 2 x 1m	11.0 km
27J.	Batter failure 4 x 10m	11.35km
Top of range		
28J.	Intermittent batter failure ~100m	12.3 km
29J.	Batter failure 1 x 1m	13.2 km

Kuranda end odometer reading 14.7 km

Barron Gorge Road, logged 9 April 1997
29AJ. Debris slide 8 x 6m (vol ~5m^3), 0.55 km from power station

30J. Debris slide 15 x 3m (vol ~2m^3), 0.2 km from power station

Toogood Road/Comet Street/Granadilla Drive, logged 9 April 1997
60J. Batter failure - rock fall 1 x 0.3m (vol << 1m^3)

60J. Batter failure - rock fall 2 x 5m (vol ~1.5m^3)

60J. Batter failure - rock fall 1 x 1m (vol ~ 0.5m^3)

60J. Batter failure - rock fall 1 x 0.5m (vol << 1m^3)

61J. Batter failures - rock falls
Three old and one new (reactivated) (vol ~0.5m^3)

61J. Rock fall 1.5 x 1.5m (vol ~1m^3) - debris still on road

61J. Debris slide 1 x 1m (vol <<1m^3) - debris still on road

61J. Batter failure - debris fall/slide - 3 x 1m (vol ~0.5m^3)

61J. Batter failure - debris fall/slide - 1 x 1m (vol <<1m^3)

61J. Reactivated batter failure (debris slide) behind house

61J. New batter failure (debris fall) on right hand side of house (small <<1m^3)

62J. Debris slide went across drive - 15 x ~2m (vol ~2m^3)

62J. Second slide on to drive ~6 x ~1m (vol ~1m^3)

63J. Small batter failure - rock fall 1 x 0.5m (vol <<1m^3)

Granadilla Drive (one lane section)
65J. New batter failure - rock fall ~1 x 1m (vol <1m^3)

Comet Street-Granadilla Drive walkway
64J. Reactivated batter failure (vol <<1m^3)

Gordonvale, logged 10 April 1997

Valley on NW side of Walsh's Pyramid - several very small rock falls/slides which may be new. They were seen only from a distance.

Freshwater Valley, Redlynch Intake Road, logged 10 April 1997

Odometer reading No. 1 crossing, Freshwater Creek 0.0 km

68J.	Batter failure 2 x 0.3m (vol <<1m^3)	0.8 km
69J.	Batter failure 5 x 5m (vol ~2m^3)	0.9 km
70J.	Batter failure 1.5 x 1m (vol <<1m^3)	1.7 km
71J.	Batter failure - just south of Rocks Road 3 x 1m (vol <<1m^3)	3.8 km
71J.	Batter failure - just south of Rocks Road 0.5 x 1m (vol <<1m^3)	3.8 km
71J.	Batter failure - just south of Rocks Road 1 x 0.5m (vol <<1m^3)	3.8 km
72J.	Debris fall/slide on near vertical batter in terrace at Jungara 3 x 1m (vol ~0.5m^3) (~ 30m N of Arthur Lyons Drive; ~100m N of Rocks Road)	4.1 km

South side of Stoney Creek Road, Rainforest Estate, logged 11 April 1997

73J. Batter failure, rock fall 2 x 1m (vol ~0.5m^3)
400m east of Jagera Ct

74J. Batter failure, debris fall 2 x 1m (vol ~0.5m^3)
Opposite Douglas Track

Escarpment on the west side of Whitfield, logged 11 April 1997

75J. A number of what appear to be small new failures
opposite Murchison Street (above Hillview Crescent)

Yarrabah Road, on east side of inlet, logged 11 April 1997
Odometer at Koombal turnoff 0.0 km

76J.	Small rock falls from cliff/batter in metamorphic rock (vol ~0.5m^3)	0.3 km
77J.	Batter failure, debris slide 10 x 3m (vol 5-10m^3)	0.45 km
77J.	Batter failure, debris fall (vol ~1m^3)	0.45 km
77J.	Batter failure, rock fall (vol ~1m^3)	0.5 km
78J.	Batter failures, rock falls/debris slides (vol <<1m^3) Reactivation of old larger batter failure ~4 x 20m in metamorphic rock, just south of Second Beach	1.55 km
78J.	Batter failure, debris fall ~3 x 0.5m (vol ~0.5m^3) in metamorphic rock	1.6 km
79J.	Batter failure, rock fall in metamorphic rock (vol ~0.5m^3)	1.9 km
80J.	Batter failures, rock falls (vol <<1m^3) Reactivation of old larger batter failure ~6 x 15m just south of Giangurra	4.3 km
81J.	Batter failure, debris fall (vol <<1m^3)	5.55 km

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APPENDIX D

BASIS FOR SHADOW ANGLES

1 Field Observations

1.1 Some shadow angles were measured at the limit of boulder sized remnant debris flows north of Ellis Beach. The debris had been winnowed by wave attack.

Two values of 24° were measured; the scarp height at this point was about 400 m.

1.2 Some general values could be initially interpreted from the South Redlynch fan complex, with a scarp height of 700 m

Limit of massive boulder core complex	18.4°
Limit of proximal debris	15.6°
Limit of distal debris	12.4°

1.3 At Smithfield Heights, scarp height of 400 m

Limit of massive boulder core complex	15.9°
Limit of distal debris	12.4°

1.4 At Lyons point, scarp height 400 m

Limit of core complex/proximal debris 17°

1.4 At Falls Creek on Yarrabah Road, height 150 m

Limit of core complex/proximal debris 12°

2 Other shadow angles in the literature

2.1 Hong Kong, by debris flow size (Wong, Ho & Chan, 1997)

< 2000 m^3	>30°
>20 000 m^3	>20°
liquefaction	> 15°

2.2 Hutchinson on the chalk

Height 50 m, angle 55°

Height 100 m, angle 18°

3 Discussion

So we can assume that the significant debris flows are in the 100 m to 500 m height range and generally > 10 000 m^3

Initially applied:

Proximal limit: 17° Distal limit: 12°.

A detailed study of the relationship between shadow angle limits at 1° intervals and geomorphological boundaries was then carried out at South Redlynch, as this is the only area in which there is any detail available. Following that study, angles were chosen of:

Proximal limit: 19° Distal limit: 14°

If anything, the limit to which debris flows could extend were slightly underestimated for the large South Redlynch debris flow complex, in order that debris flow hazard for the entire Cairns area was not unduly exaggerated.

APPENDIX E

DEFINITIONS USED IN THIS LANDSLIDE RISK ASSESSMENT

Elements at risk: Those parts of the community which may be adversely affected by landslides. In this report, we have considered, separately, people, buildings and roads.

Hazard: The probability of impact of a landslide at a given point in the study area in a specified period of time (usually one year). The hazard varies between 0 (no probability of impact by a landslide) and 1 (impact by a landslide is certain). It can also be expressed as a ratio, such as 1 in 10 (0.1), 1 in 100 (0.01), 1 in 1000 (0.001), 1 in 10 000 (0.0001), 1 in 100 000 (0.00001) and 1 in 1 000 000 (0.000001).

Landslide event: A set of geographically closely spaced landslides triggered by the same rainfall event.

Polygon: In this report a polygon is taken to be a geomorphic unit as shown on the landslide data map. Examples of polygons mentioned in the risk assessment are:
b1 - fall faces or steep slopes with cliff lines, developed in bedrock,
b2 - transportational midslopes developed as ridges and gullies in bedrock,
b3 - bedrock footslopes sometimes locally covered with sediment,
fc - massive core debris flow deposits with irregular lobate surface, numerous boulders greater than 1 m long,
fp - proximal debris flow fan/outwash with gentle undulating convex slope forms, and
fd - distal outwash fan with uniform low angle slopes.

Recurrence interval: The mean time interval between landslide events with a volume equalling or exceeding a given value.

Specific risk: The probability, at a given point in the study area, that an element at risk may be destroyed by a landslide. It is equal to the hazard multiplied by the vulnerability. Like hazard, its value varies between 0 and 1. We have assessed the specific risk for people, buildings and roads separately. We have also assessed the probability of any 10 km stretch of road, parallel to the escarpment, being temporarily closed somewhere along its length by a landslide.

Total risk: The total number of people expected to be killed, or buildings destroyed, in a given area in a specified period of time by landslides. In this report we have also considered the number of people expected to be killed, or buildings destroyed, per square km per 100 years

Vulnerability: The probability of an element at risk being destroyed by a landslide, given that it is impacted by the landslide. The vulnerability varies between 0 (no damage) and 1 (total destruction) for a single element at risk. For a group of similar elements at risk, a vulnerability of 0 would imply that none would be expected to be destroyed, and for a vulnerability of 1, all would be expected to be destroyed. If the vulnerability were 0.5, half of them would be expected to be destroyed.

APPENDIX F

RECURRENCE INTERVALS FOR LANDSLIDES ON DEVELOPED HILLSLOPES PER 10 KM OF SCARP
Figure 11(b)

1 year event
Assume the observations logged while driving along Lake Morris Road on 5 March 1997 occurred in the one year rainfall event.

Volume of new batter failures = 48 m^3 in 14.5 km of road
= 33 m^3 in 10 km of road

Log V = 1.52

This is from observations along a single road in an otherwise natural slope, and the recurrence relation is plotted in Figure 11(a).

If the whole escarpment were to be developed, assume that there is a network of roads 100m apart, the approximate spacing between roads in suburban Cairns.

Then 33 m^3 approximates the failure volume of an area of the escarpment 10 km long and 100 m wide, an area of 1 000 000 m^2.

The total area of b1/b2/b3 per 10 km of escarpment is 15 090 000 m^2. Hence, the failure volume per 10 km of developed escarpment would be
33 x 15 090 000/1 000 000 m^3 = 498 m^3.

Log V = 2.70, number per year = 1.0.

T.C. *Justin* - the 2.3 year rainfall event. Recurrence interval deduced from Met Office rainfall recurrence table
Number of events per year is 0.43

From logs made while driving along Lake Morris Drive and Kuranda Range Road, mean length/height of a single landslide is 3.5m. This is the total length of the failure surface plus the runout. From two photographs of batter failures, one on Kuranda Range Road and the other on the Barron Gorge Road, just under half the total length of the landslide comprised the runout. Therefore, assume that the mean length/height of the failure surface, excluding the runout, is 2 m.

The *maximum failure rate* was observed along Kuranda Range Road.
From observations along Kuranda Range Road, slope width failure rate is 1.8% = 180m/10km scarp.
Assume mean failure thickness = 0.3 m.
Mean failure height = 2 m.

V = failure volume/10km road = 2 x 180 x 0.3 m^3
= 108 m^3

Log V = 2.03

This is from observations along a single road in an otherwise natural slope, and the recurrence relation is plotted in Figure 11(a).

If the whole escarpment were to be developed, assume that there is a network of roads 100m apart, the approximate spacing between roads in suburban Cairns.

Then 108 m^3 approximates the maximum failure volume of an area of the escarpment 10 km long and 100 m wide, an area of 1 000 000 m^2.

The total area of b1/b2/b3 per 10 km of escarpment is 15 090 000 m^2. Hence, the maximum failure volume per 10 km of developed escarpment would be
108 x 15 090 000/1 000 000 m^3 = 1630 m^3 = V.

Maximum log V = 3.21

From observations of suburban b1/b2/b3, there was a total of 8 m^3 failure volume in a total developed area of 8 149 000 m^2.
The total area of b1/b2/b3 per 10 km of escarpment is 15 090 000 m^2.
Hence, V = minimum failure volume/10km scarp = 8 x 15 090 000/8 149 000 m^3
= 14.8 m^3

Minimum log V = 1.17

log V per 10 km scarp =1.17 - 3.21, number per year = 0.43

T.C. *Rona*, 11 February 1999
296 mm of rain in 24 hours = 12.3 mm/hr for 24 hours
3.9 year average recurrence interval
Number of events per year = 0.26

Landslides logged along Kuranda Range Road:
Total failure volume = 236.9 m^3 in 13.2 km
= 179.5 m^3 in 10 km

Log V = 2.25

This is from observations along a single road in an otherwise natural slope, and the recurrence relation is plotted in Figure 11(a).

If the whole escarpment were to be developed, assume that there is a network of roads 100m apart, the approximate spacing between roads in suburban Cairns.

Then 179.5 m^3 approximates the maximum failure volume of an area of the escarpment 10 km long and 100 m wide, an area of 1 000 000 m^2.

The total area of b1/b2/b3 per 10 km of escarpment is 15 090 000 m^2. Hence, the maximum failure volume per 10 km of developed escarpment would be
179.5 x 15 090 000/1 000 000 m^3 = 2709 m^3 = V.

Log V = 3.43

From observations of suburban b1/b2/b3, there was a total of 11.3 m^3 failure volume in a total developed area of 8 149 000 m^2.
The total area of b1/b2/b3 per 10 km of escarpment is 15 090 000 m^2.
Hence, V = failure volume/10km scarp = 11.3 x 15 090 000/8 149 000 m^3
= 20.9 m^3

Log V = 1.32

log V per 10 km scarp =1.32 - 3.43, number per year = 0.26

1 April 1911 rainfall event - the 50 year event.
Failures along 14.5 km of Cairns-Kuranda Railway.
Recurrence interval deduced from Met Office rainfall recurrence table.
Number of events per year = 0.02

Landslide GIS No. in Cairns Database	*Volume m^3 (? = size unknown)*
11	?400
12	?400
13	400
3	?400
14	?400
5	600
15	200
16	?600

Total volume per 14.5 km of railway = 3400 m^3

Volume per 10 km of railway = 2430 m^3

Log V = 3.38

This is from observations along a single railway in an otherwise natural slope, and the recurrence relation is plotted in Figure 11(a).

If the whole escarpment were to be developed, assume that there is a network of roads 100m apart, the approximate spacing between roads in suburban Cairns.

Then 2430 m^3 approximates the failure volume of an area of the escarpment 10 km long and 100 m wide, an area of 1 000 000 m^2.

The total area of b1/b2/b3 per 10 km of escarpment is 15 090 000 m^2 . Hence, the failure volume per 10 km of developed escarpment would be
2430 x 15 090 000/1 000 000 m^3 = 36 700 m^3.

log V per 10 km scarp = 4.56, number per year = 0.02

10 000 year event: Assume torrential rainfall over the entire map area

For minimum failure volume per 10 km of scarp, assume a failure depth of 1 m.
Area of 10 km of scarp = 830 x 10 000 m^2 = 8 300 000 m^2
For debris flow producing landslides, failure area = 360 000 m^2 approx.
Area of scarp not involved in debris flow producing landslides = 8 300 000-360 000 m^2
= 7 940 000
Assume failed area = 0.2 x 7 940 000
Failure volume for non debris flow producing landslides = 0.2 x 7 940 000 x 1 m^3
= 1 588 000 per 10 km of scarp
Minimum total volume of landslides per 10 km of scarp = 1 588 000 + 360 000 m^3
= 1 948 000 m^3
Minimum log V = 6.29

For maximum failure volume, assume 0.25 of non debris flow producing slope fails to a depth of 2 m, and that the debris flows had a 2 m failure depth and double the failure width than for the minimum volume assumption. This makes the maximum debris flow volume 4 times the minimum volume.

Failure volume for non debris flow producing landslides = 7 940 000 x 2 x 0.25 m^3 per 10 km of scarp = 3 970 000
Maximum failure volume for all landslides per 10 km of scarp = 3 970 000 + 1 440 000 m^3
= 5 410 000 m^3
Maximum log V = 6.73

log V per 10 km scarp = 6.29 - 6.73, number per year = 0.0001

Shed rate per 10 000 years per 10 km of scarp
Estimate 5 km retreat in 50 million years.
Assuming the average height of the escarpment is 500 m,
this is equivalent to 5 000 000 m^3 per 10 000 years per 10 km of scarp.

log V = 6.70 ***This is near the upper limit of the range calculated above, suggesting that those figures are of the correct order of magnitude.***

APPENDIX G

RECURRENCE INTERVALS FOR DEBRIS FLOWS
Figure 12

Three debris flows in 120 years with a volume greater than or equal to the minimum volume.
Number per year = 0.0248 for 122 km of scarp

The events are: 1878 on eastern side of inlet - multiple landslides, volume unknown
1911 Nisbet Range and maybe Giangurra inlet (photo taken from Cairns)
Volume at least 5000 – 130 000 m^3
1951 Ellis Beach, volume ca. 360 000 m^3

Estimate of volume = 5000 – 130 000 m^3
log volume = 3.70 - 5.11
Number of debris flow events per year of at least this volume in 122 km of scarp = 0.0248
Number of debris flow events per year of at least this volume in 10 km of scarp
= 0.0248x10/122
= 0.00203

log volume = 3.70-5.11, number per year per 10 km of scarp = 0.00203

Ellis Beach, 1951
700 mm of rain in just under 5 hours.
Cairns Airport and Kuranda railway station meteorological records do not extend to such a high rainfall intensity.
Extrapolation of Cairns Airport meteorological records gives a return period of the order of 10 000 years, which fails the reasonableness test.
Extrapolation of Kuranda railway station meteorological data (daily rainfall) gives a return period of about 400 years, which appears to be more believable.
Assume the return period of the Ellis Beach debris flow event is 400 years.
Number per year = 0.0025 for 122 km of scarp
Number per year for 10 km of scarp = 0.0025x10/122 = 0.000205

Estimate of total volume of debris flows = 360 000 m^3
For error bars, estimate could be half or double this value, i.e. 180 000 – 720 000 m^3

log volume = 5.26 - 5.86, number per year per 10 km of scarp = 0.000205

The 10 000 year event: assume torrential rain over the entire map area, and that debris flows occur *uniformly* throughout the map area.
Number per year = 0.0001

For minimum failure volume, assume a failure depth of 1m.
By inspection of stream flow patterns and debris flow material on map,
total volume = 4 390 000 m^3
Volume per 10 km of scarp = 4 390 000 x 10/122 = 360 000 = V

Minimum log V = 5.56

For maximum failure volume for debris flows, assume failure width is doubled and failure depth is 2 m.

Maximum log V = 5.56 + 0.3 + 0.3
Maximum log V = 6.16

log V = 5.56 - 6.16, number per year per 10 km of scarp = 0.0001

Plate 1. These trees are growing on the upper part of the remaining (northern) wall of Dead Man's Cutting at Riverstone (now part of Gordonvale), where five men were killed in a cave-in in 1900. The cutting was partly bulldozed in the 1980s. Walshs Pyramid is in the background. The photo was taken in 1999.

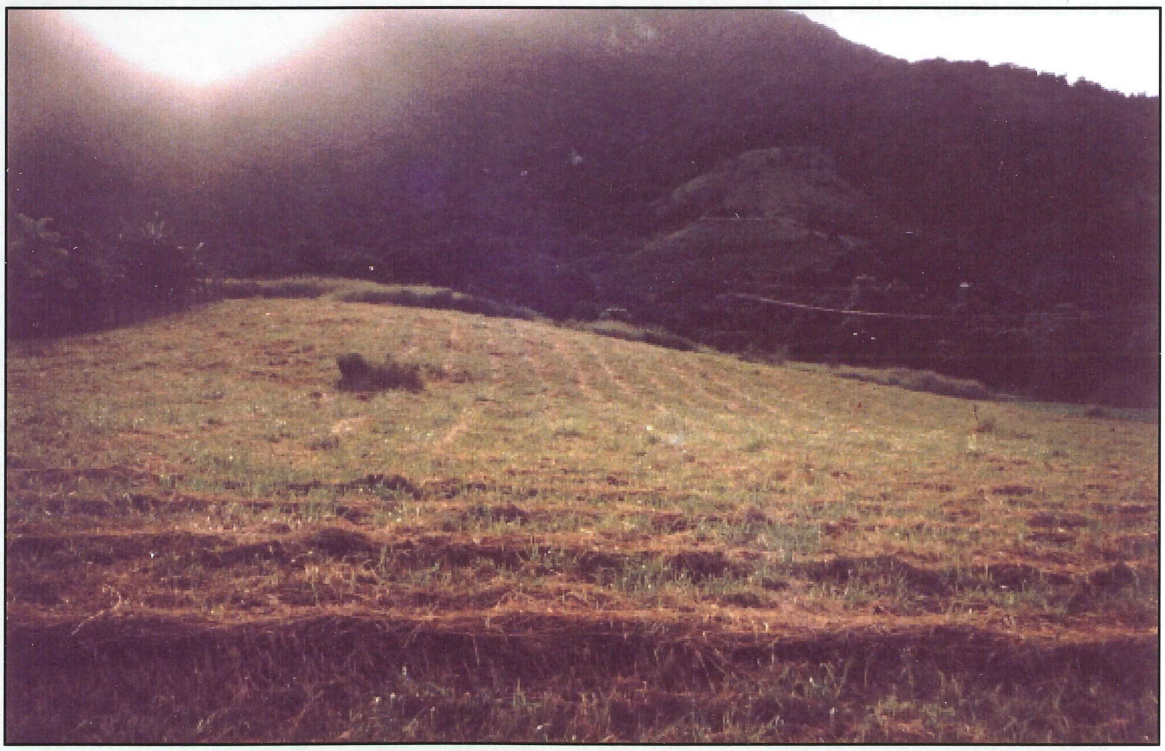


Plate 2. The gently sloping land in front of the escarpment is part of the proximal portion of the South Redlynch fan complex in Freshwater Valley.

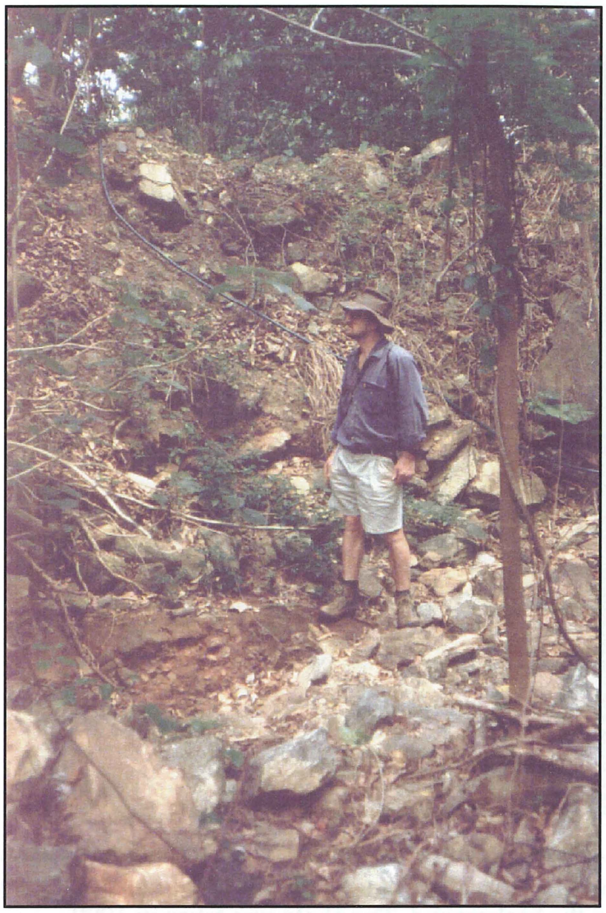


Plate 3. Proximal debris flow deposits in bank of creek in South Redlynch fan, just east of Harvey Road.

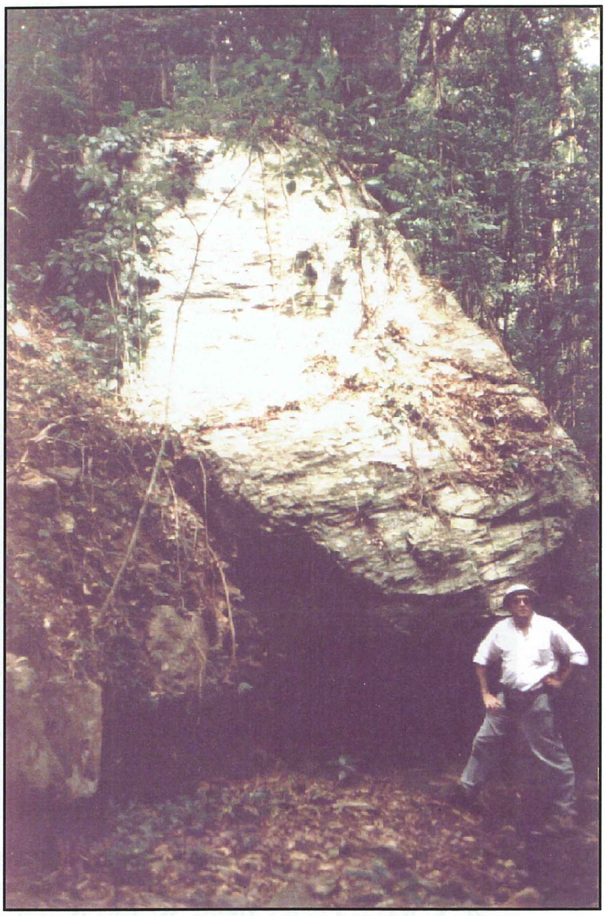


Plate 4. Large debris flow boulder in bank of creek in South Redlynch fan, just west of Harvey Road.

Plate 5. Debris, on the landward side of the Captain Cook Highway behind Ellis Beach, from one of the 1951 debris flows. The photo was taken in 1997.

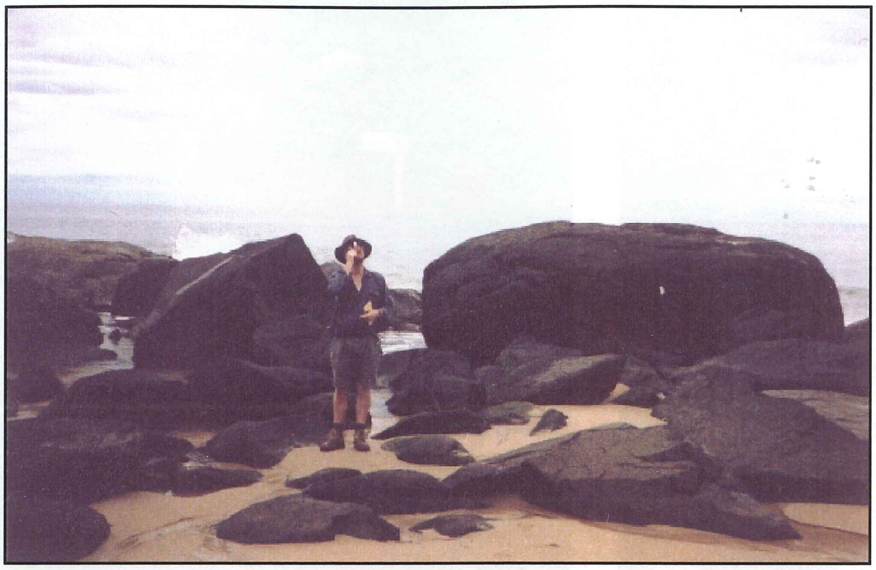


Plate 6. Boulders deposited on Ellis Beach by the 1951 debris flows. The photo was taken in 1997.

Plate 7. Landslide in Bayview Heights triggered by rain from Tropical Cyclone 'Justin' in March 1997.

Plate 8. During Tropical Cyclone 'Joy' in December 1990 a landslide to the left of the steel fence in the centre foreground severed the traffic connection between Granadilla Drive in the foreground and Comet Street, Bayview Heights, near the centre of the photo. The two roads are now connected by only a footpath.

Plate 9. One of 46 batter failures on Kuranda Range Road, triggered by rain brought by Tropical Cyclone 'Justin' in March 1997.

Plate 10. Fill failure on Lake Morris Road, triggered by the heavy rain in March 1999.

Plate 11. Rain on 26 February 1999 triggered this 500 cubic metre rock topple/fall near the Smithfield end of the Kuranda Range Road. The landslide was still active the next morning, when this photo was taken.

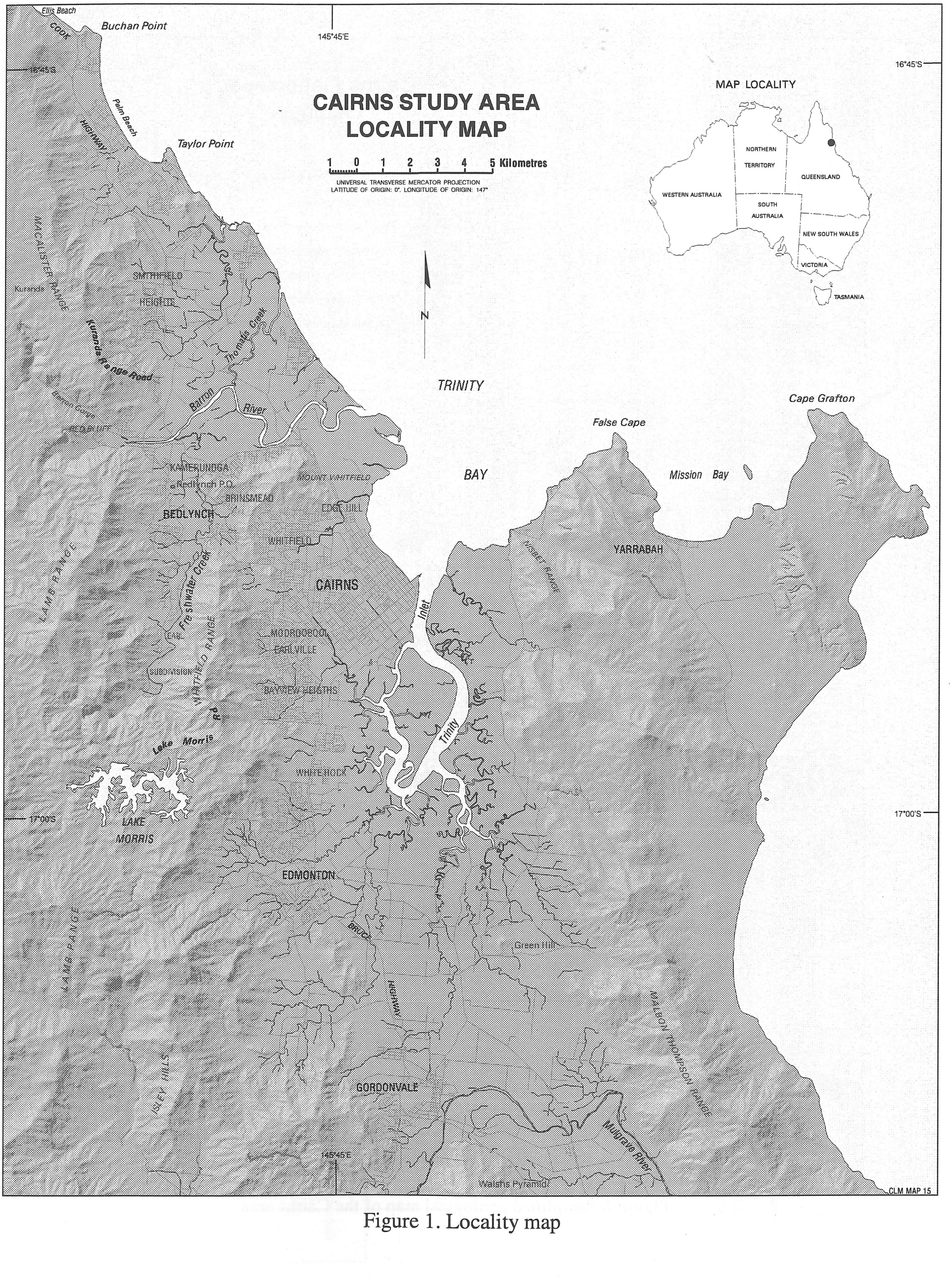


Figure 1. Locality map

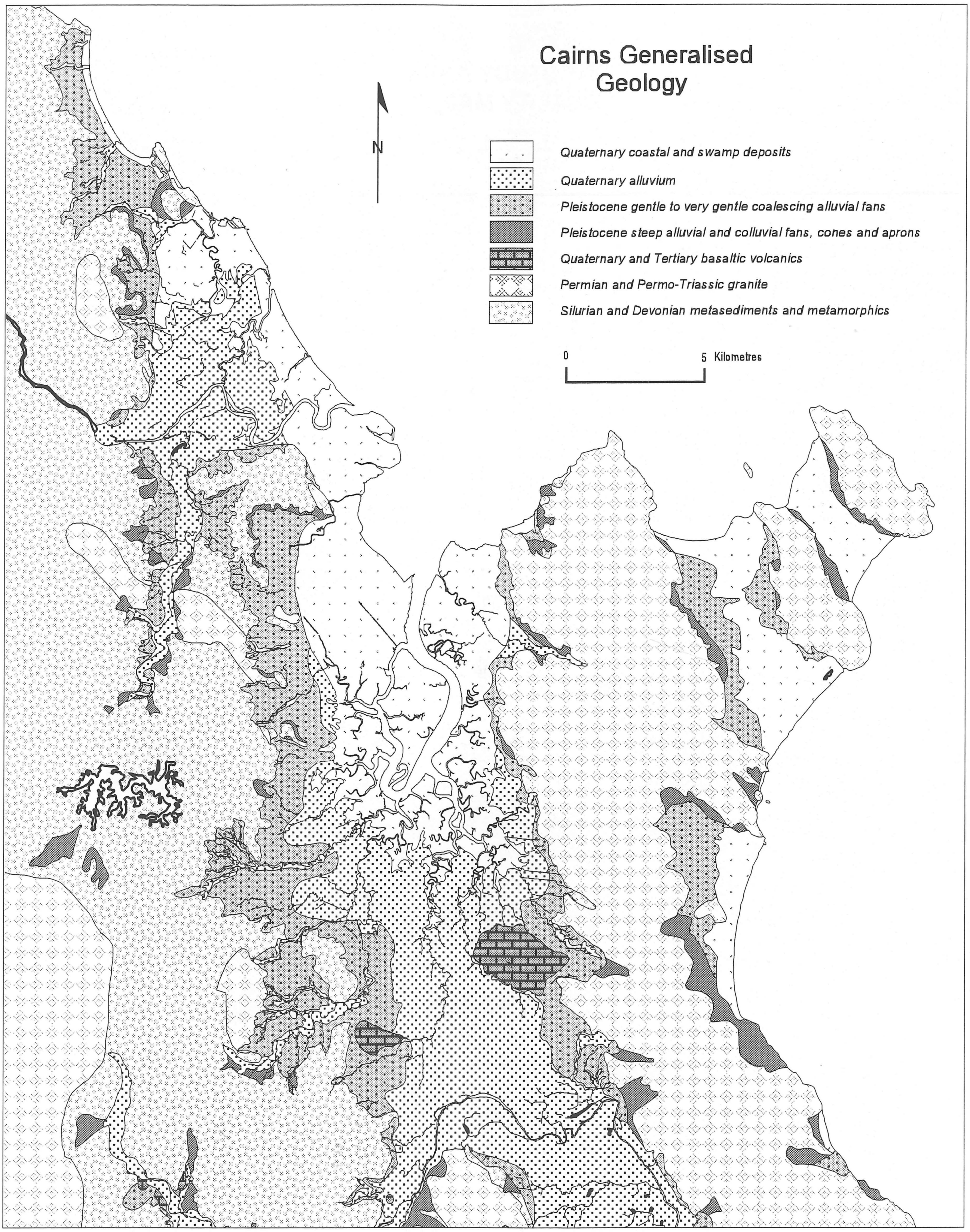


Figure 2. Simplified geological map of the Cairns area

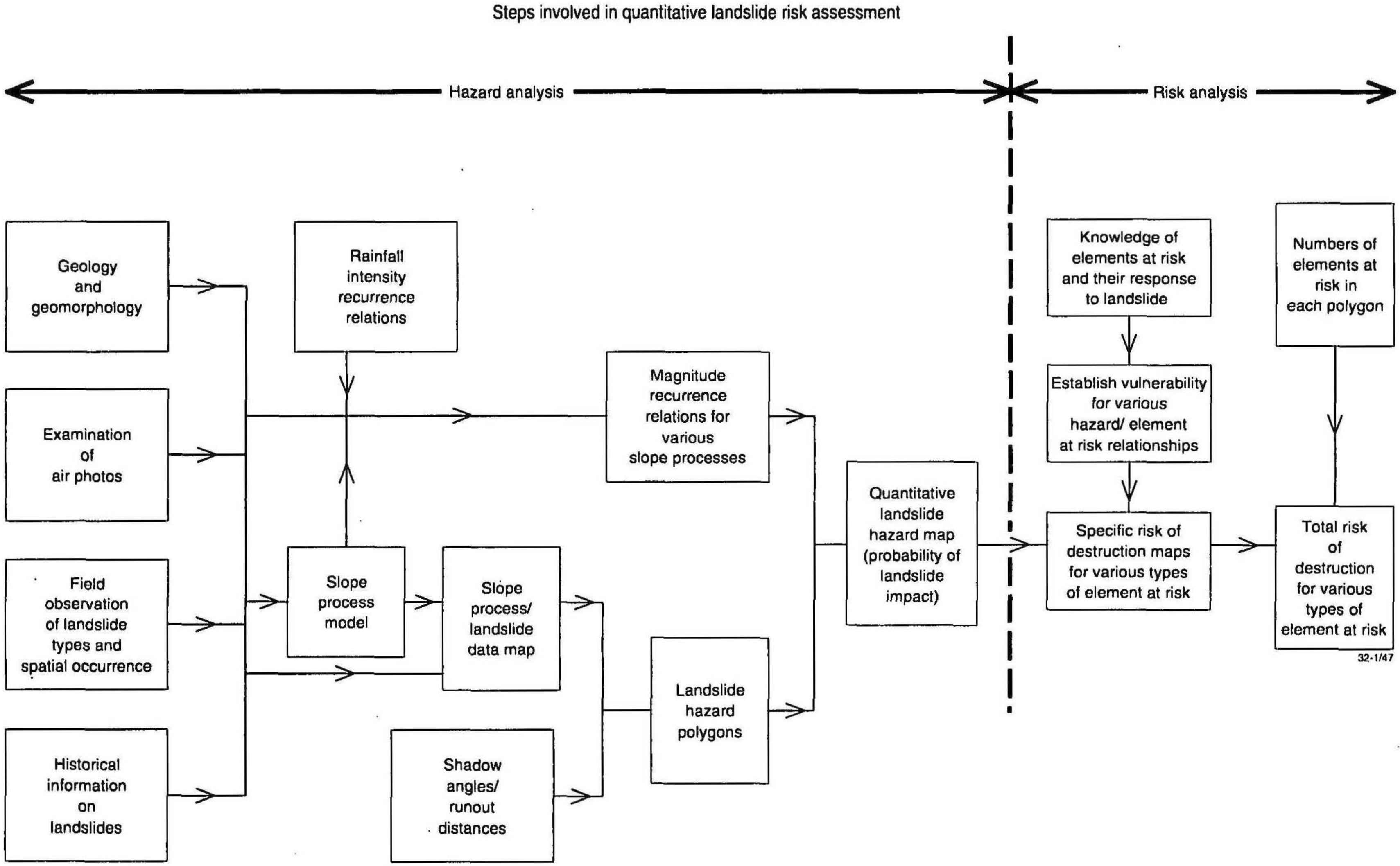
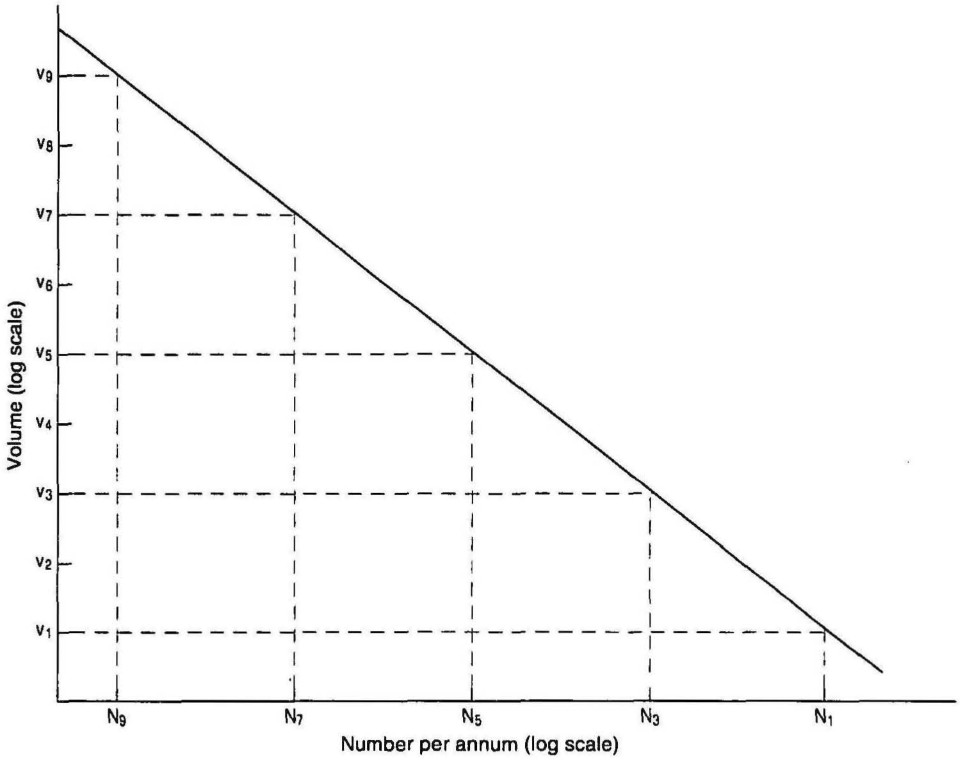


Figure 3. Quantitative landslide risk assessment process



Volume interval	Number of landslide events in volume interval	Mid-point on graph of volume interval	Area of landslide = vol/thickness $=v_2$/thickness, etc	Probability of impact at a specified point in a polygon with area $A_{polygon}$, given that a landslide happens in the polygon	Hazard = annual probability of impact at a specified point
v_1 to v_3	$N_1 - N_3$	v_2	A_2	$P_2 = A_2 / A_{polygon}$	$P_2\ (N_1 - N_3)$
v_3 to v_5	$N_3 - N_5$	v_4	A_4	$P_4 = A_4 / A_{polygon}$	$P_4\ (N_3 - N_5)$
v_5 to v_7	$N_5 - N_7$	v_6	A_6	$P_6 = A_6 / A_{polygon}$	$P_6\ (N_5 - N_7)$
v_7 to v_9	$N_7 - N_9$	v_8	A_8	$P_8 = A_8 / A_{polygon}$	$P_8\ (N_7 - N_9)$
					Sum of this column = H

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H = hazard = probability per annum of impact of a landslide (volume in the range v_1 to v_9) at any point in the polygon

$= P_2(N_1 - N_3) + P_4(N_3 - N_5) + P_6(N_5 - N_7) + P_8(N_7 - N_9)$

V = vulnerability = probability of an element at risk being destroyed by a landslide, if impacted

E = number of elements at risk in a polygon

Specific risk = H*V = annual probability of a given element being destroyed by a landslide

Total risk = H*V*E = number of elements per annum expected to be destroyed by a landslide

Figure 4. Risk assessment from magnitude recurrence graph

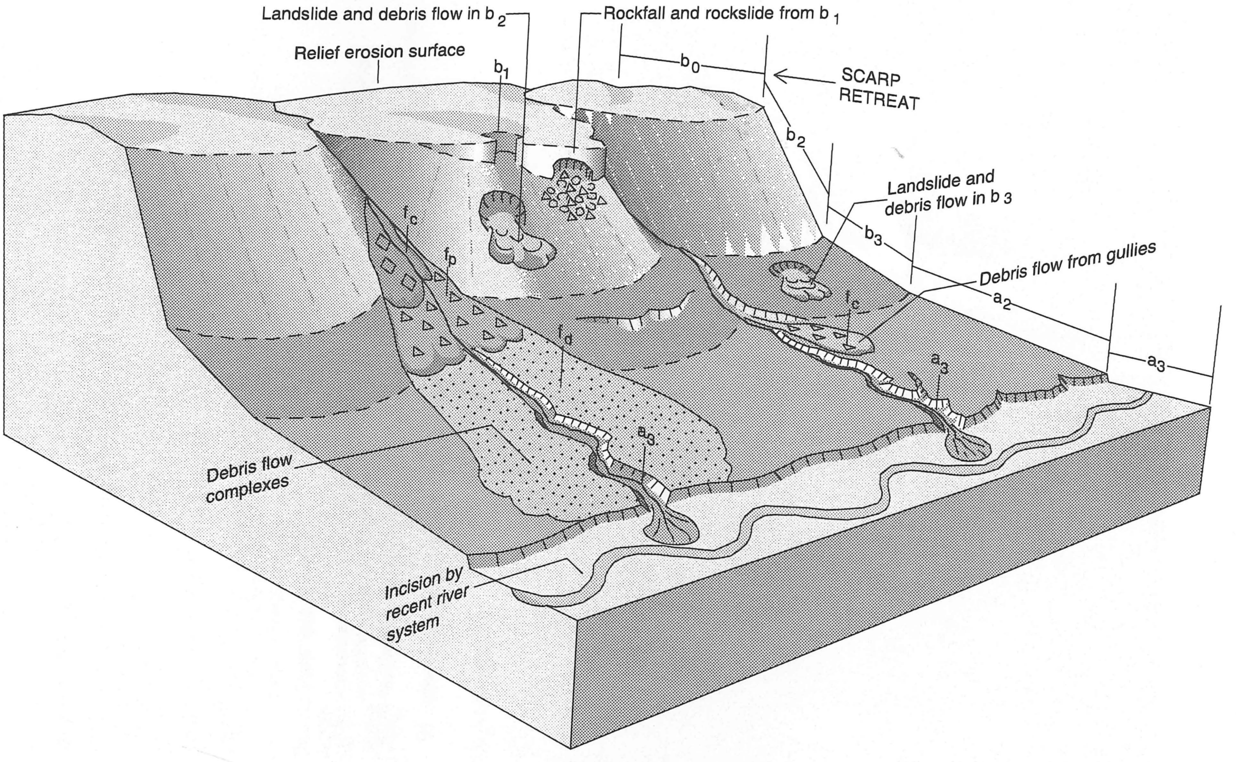

Figure 5. Slope process model

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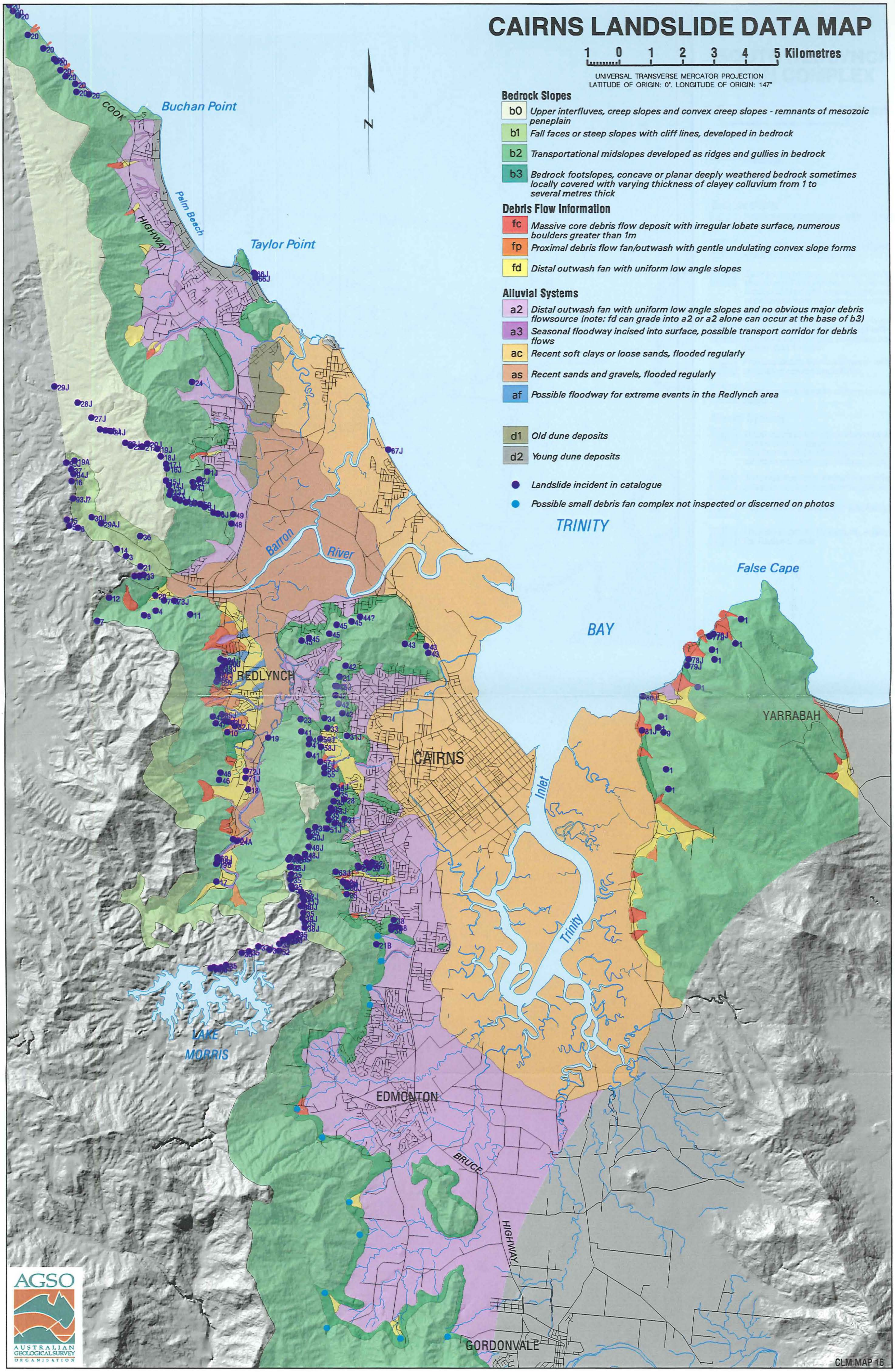

Figure 6. Landslide data map

Figure 7. South Redlynch fan

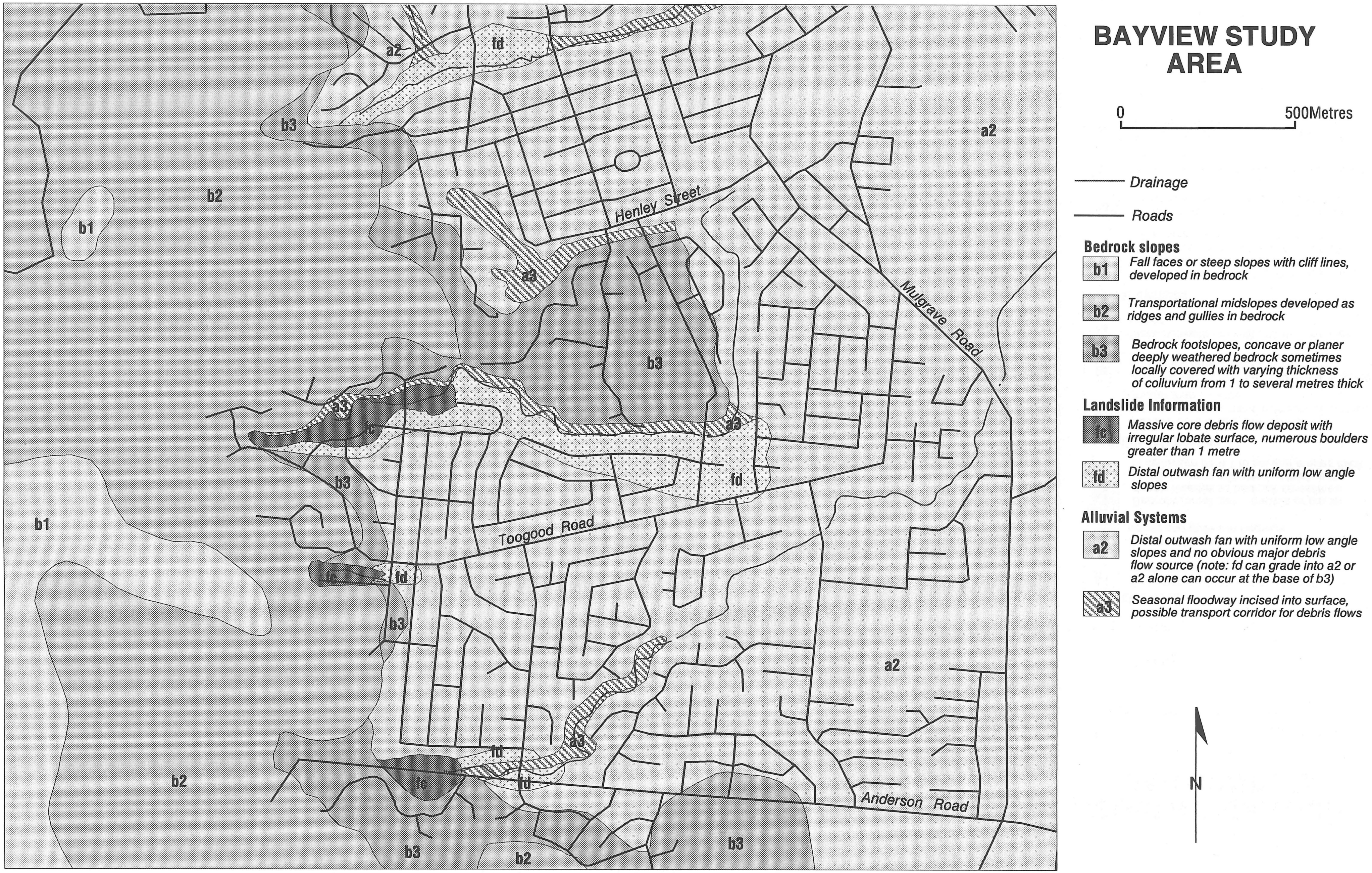

Figure 8. Bayview Heights fan

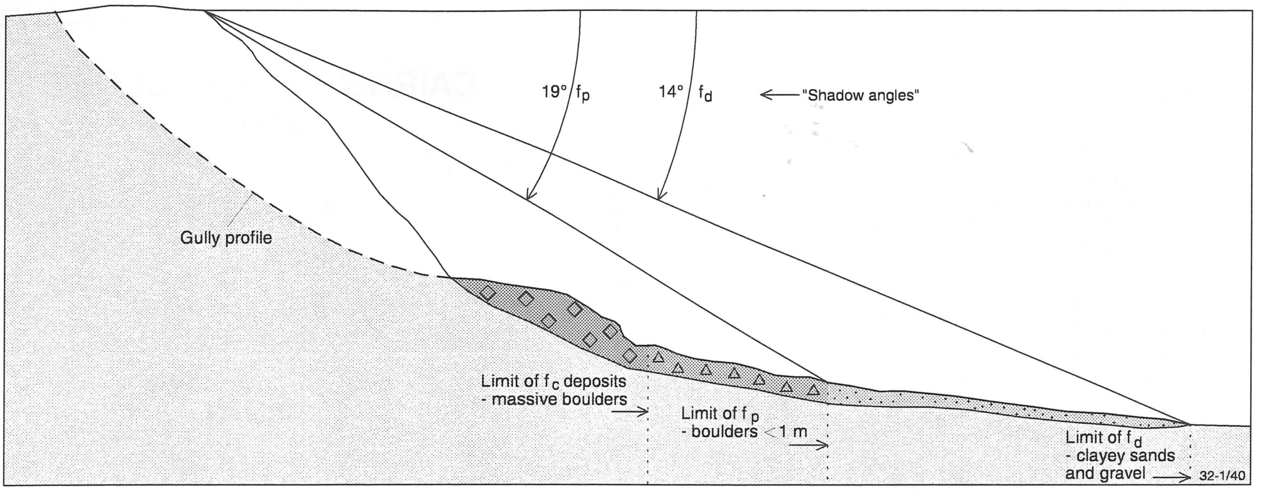

Figure 9. Shadow angles

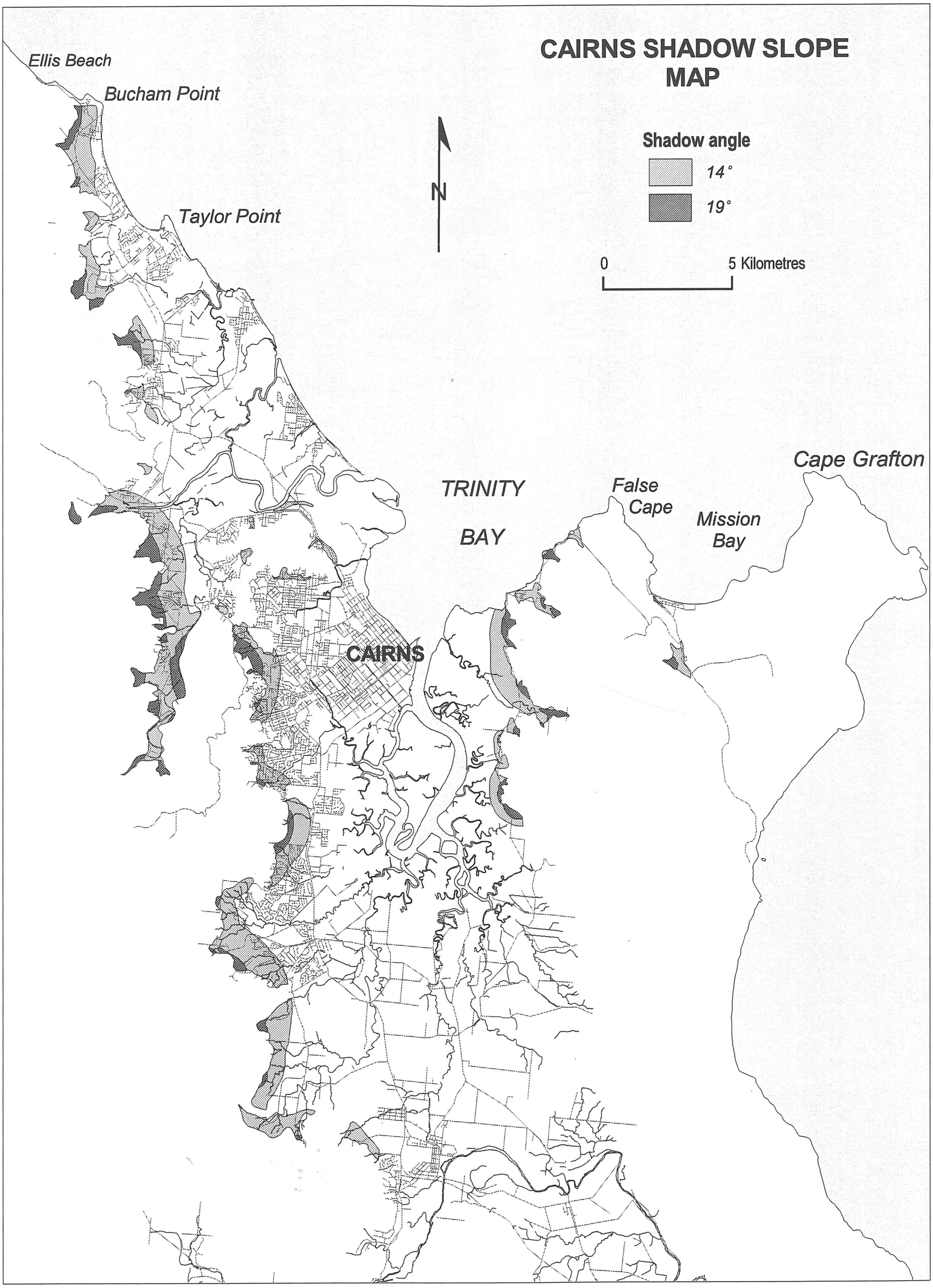

Figure 10. Cairns shadow slopes map

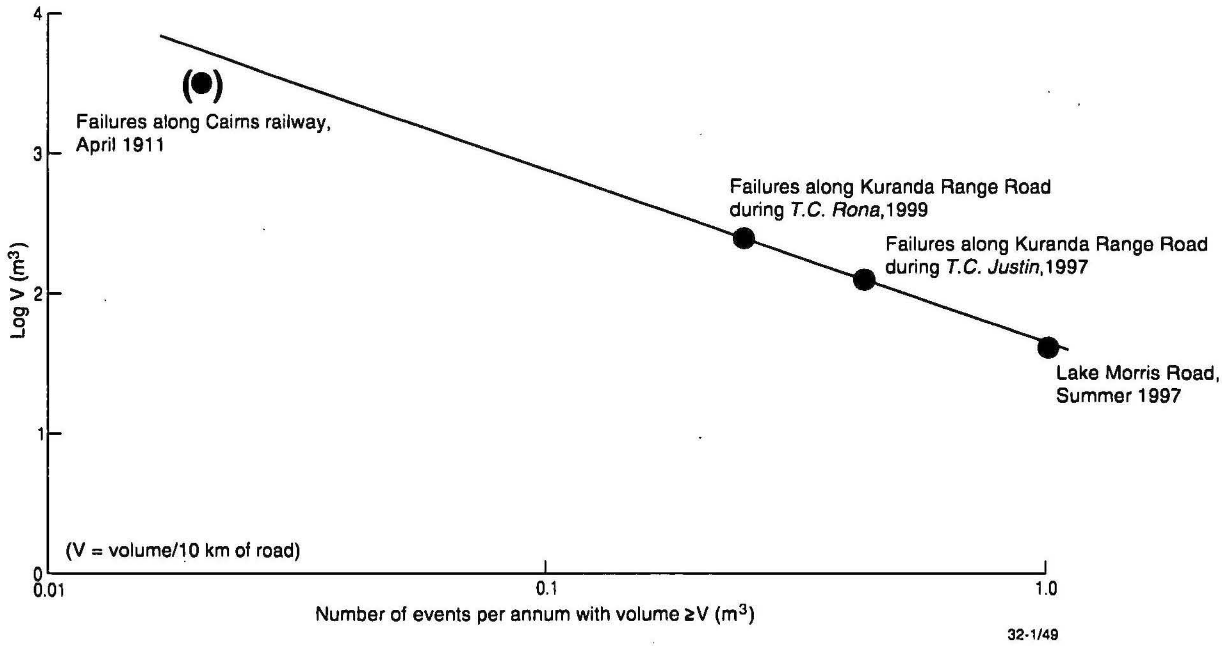

Figure 11(a). Recurrence of landslides along roads and railway along the escarpment

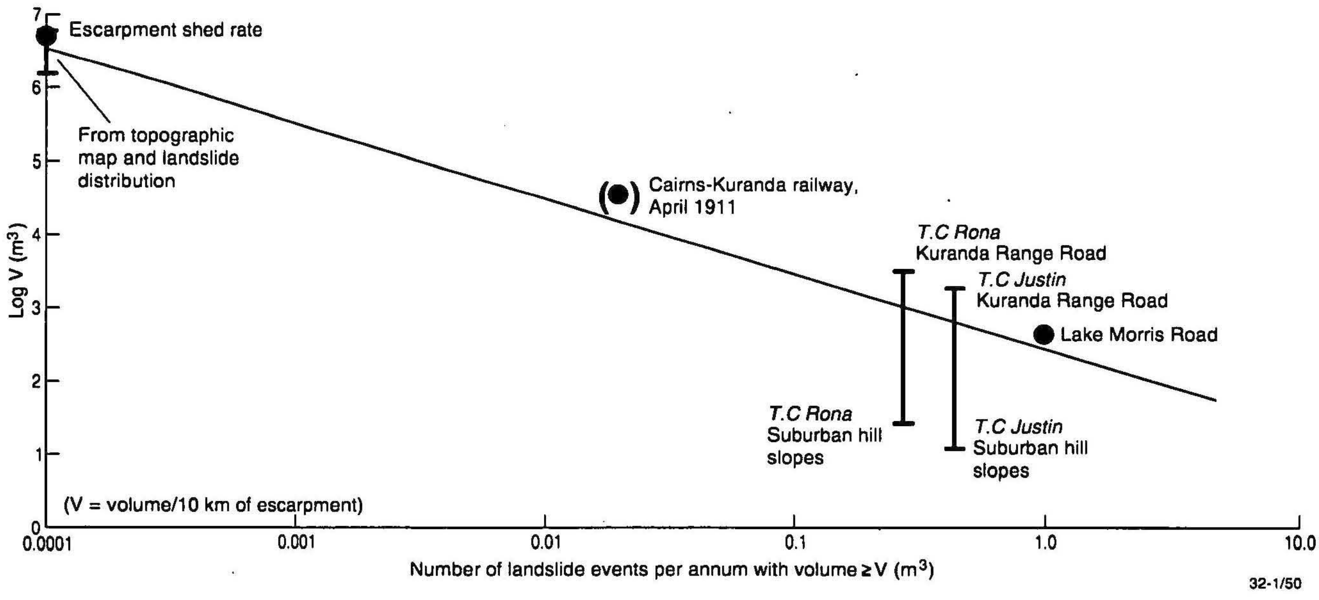

Figure 11(b). Recurrence of landslides on hill slopes

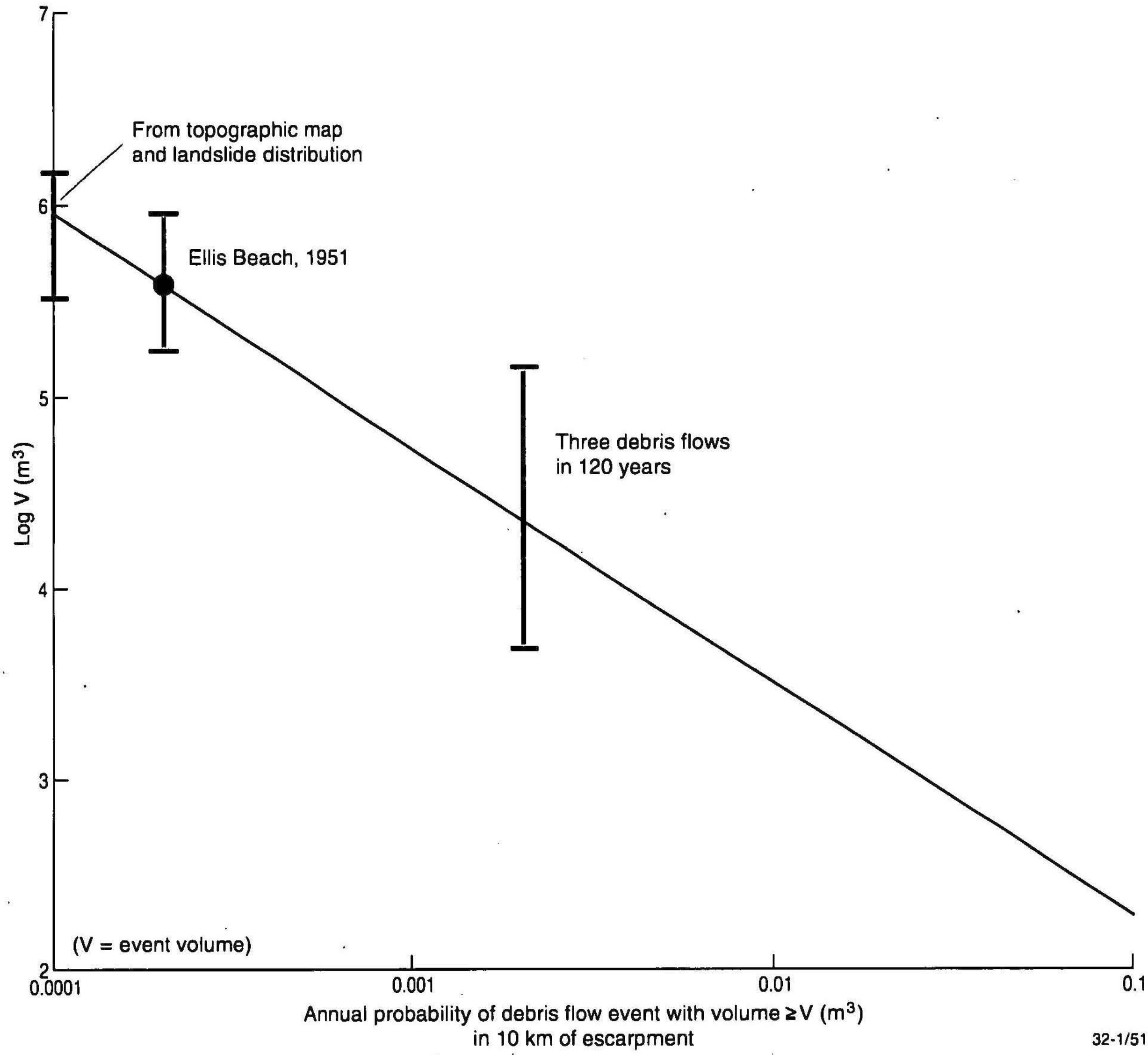

Figure 12. Recurrence of debris flows

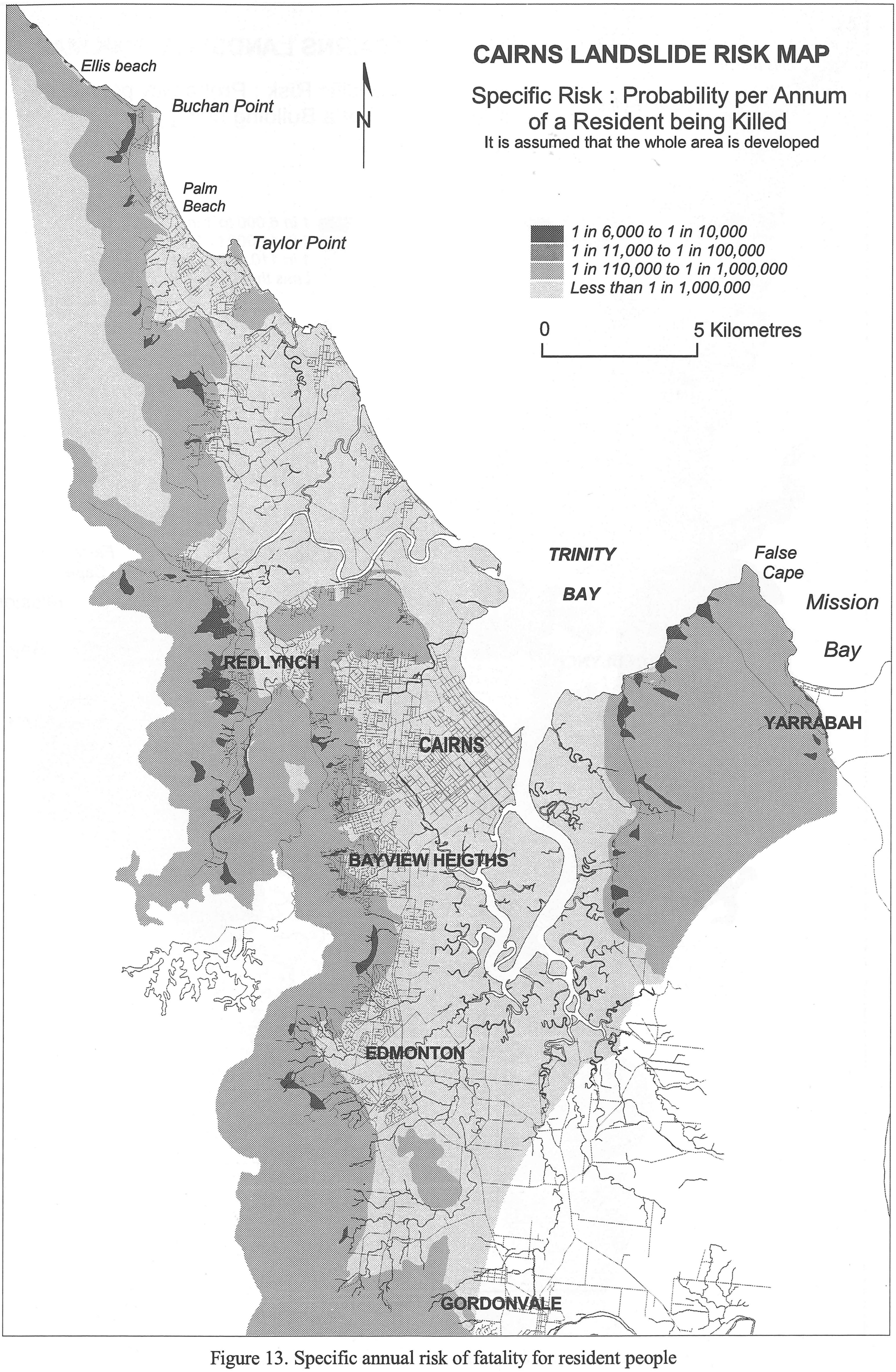

Figure 13. Specific annual risk of fatality for resident people

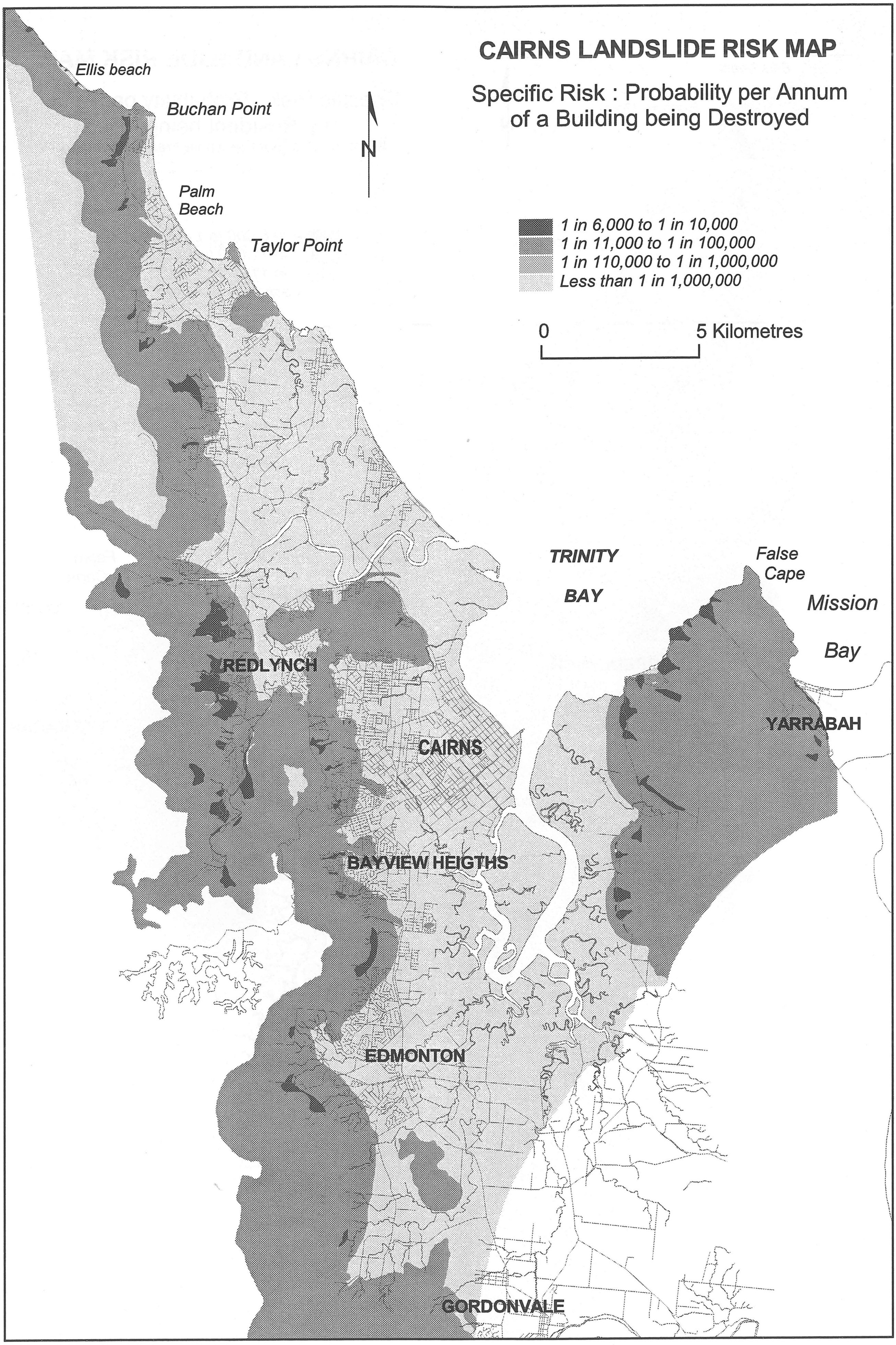

Figure 14. Specific annual risk of destruction of buildings

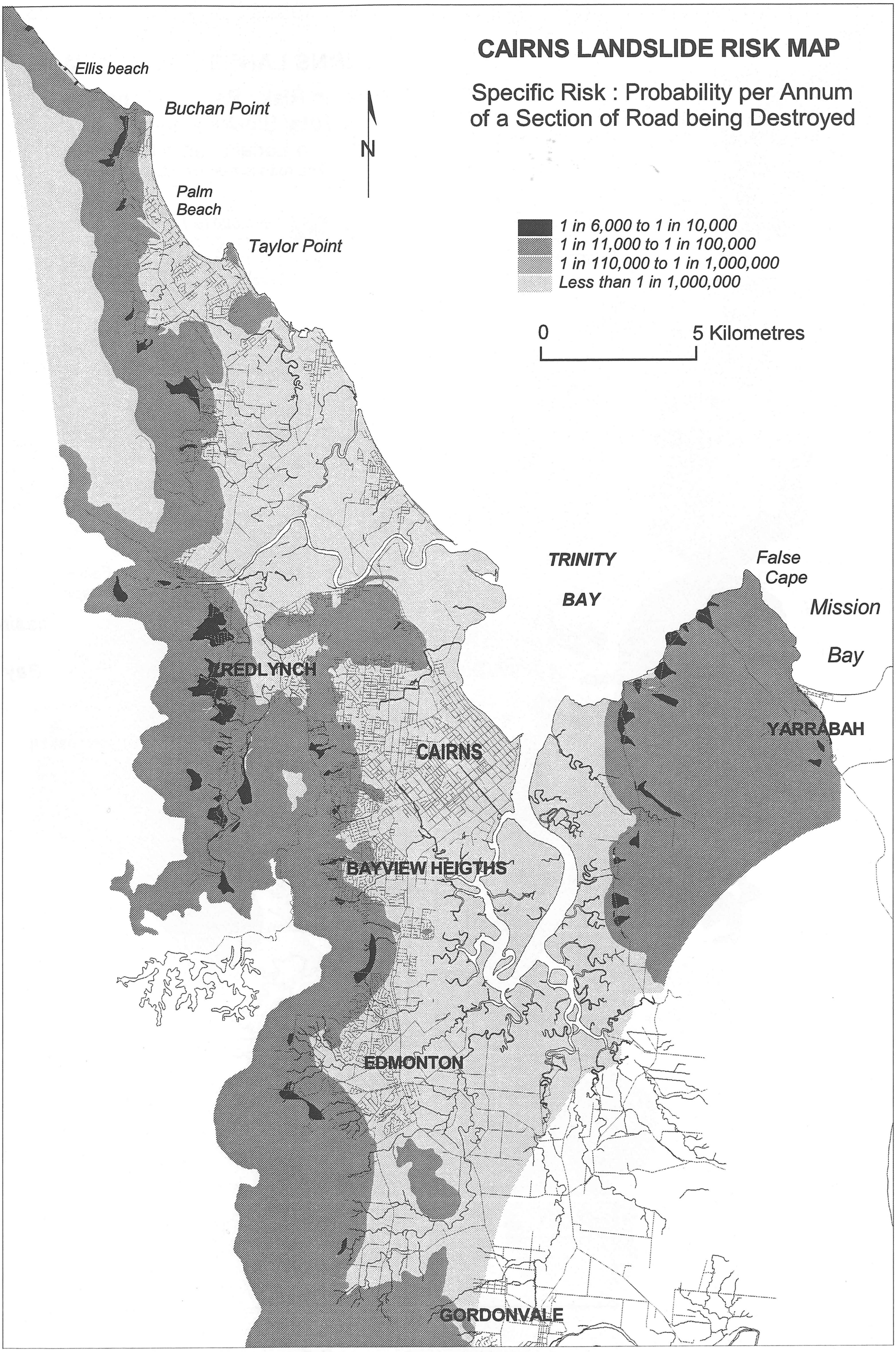

Figure 15. Specific annual risk of destruction of sections of road

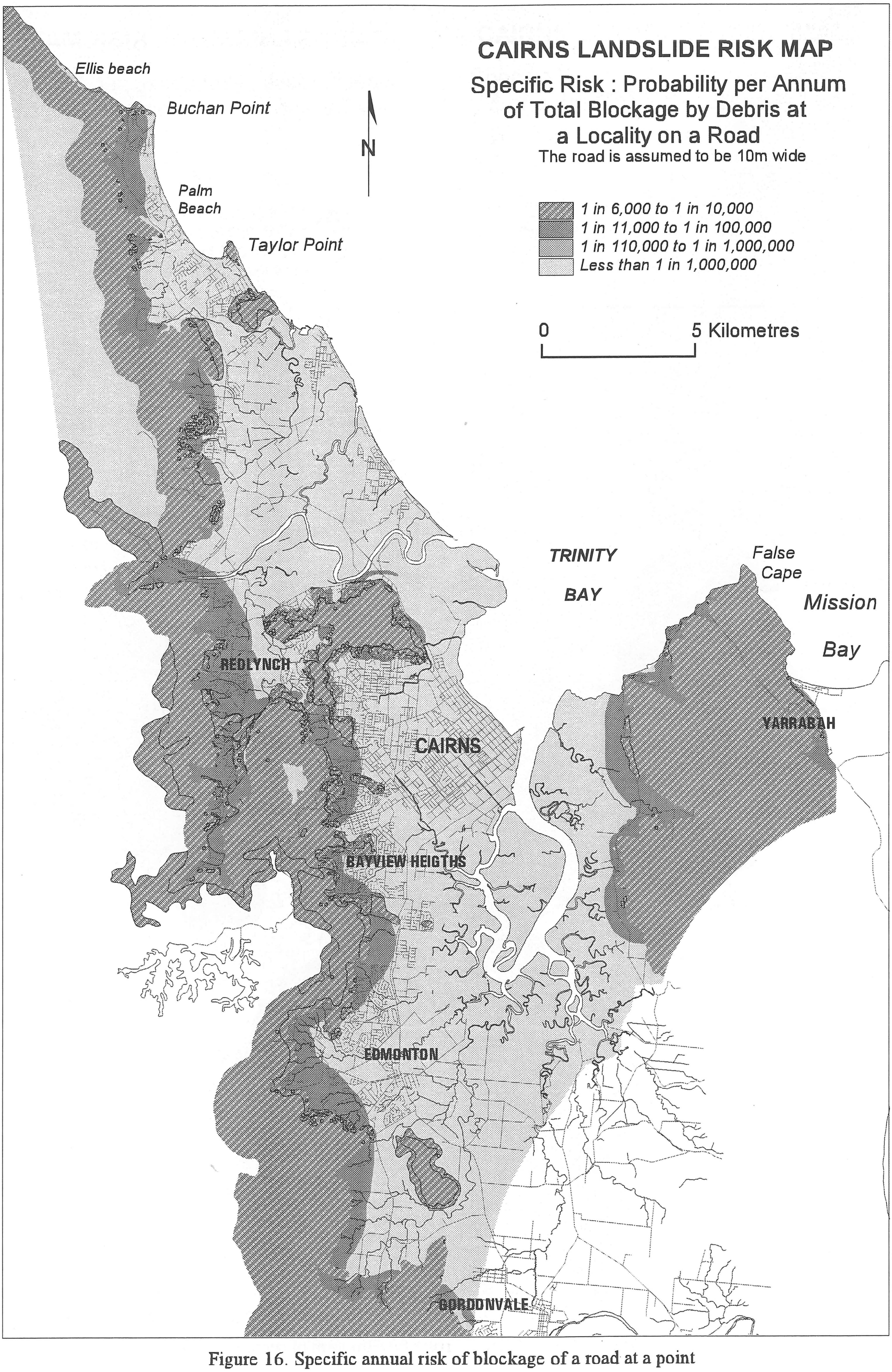

Figure 16. Specific annual risk of blockage of a road at a point

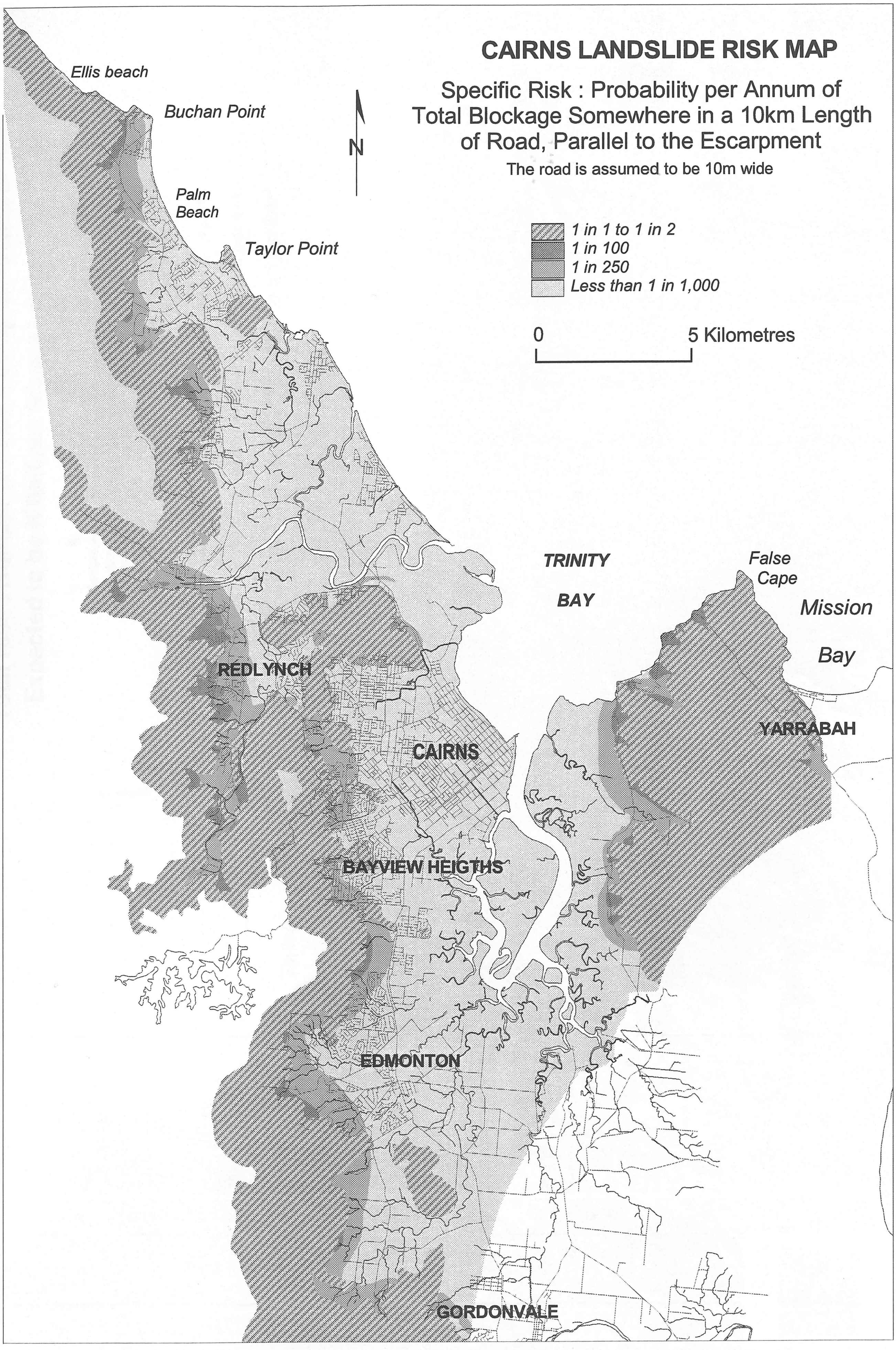

Figure 17. Specific annual risk of blockage in a 10 km length of road parallel to the escarpment

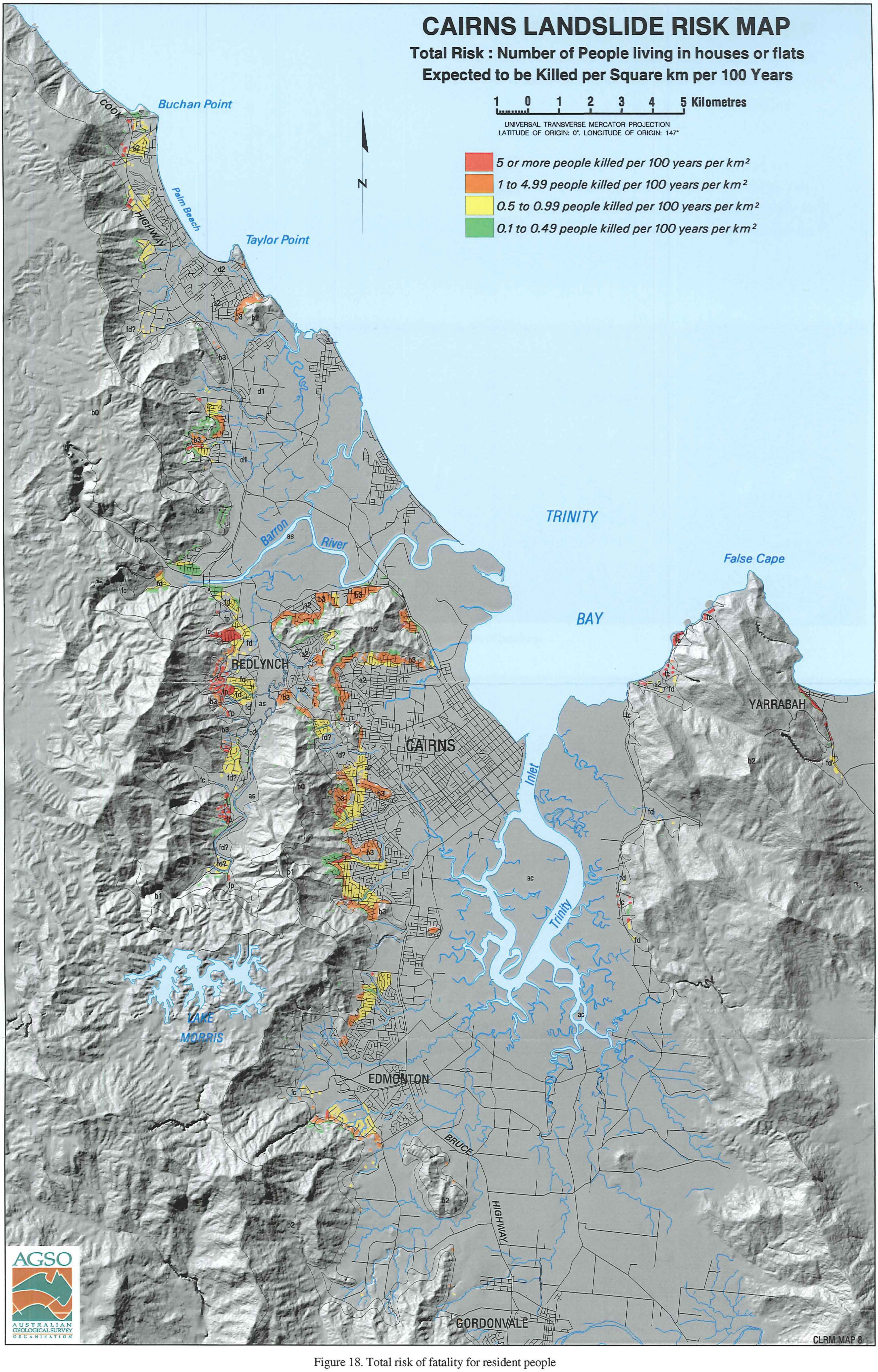

Figure 18. Total risk of fatality for resident people

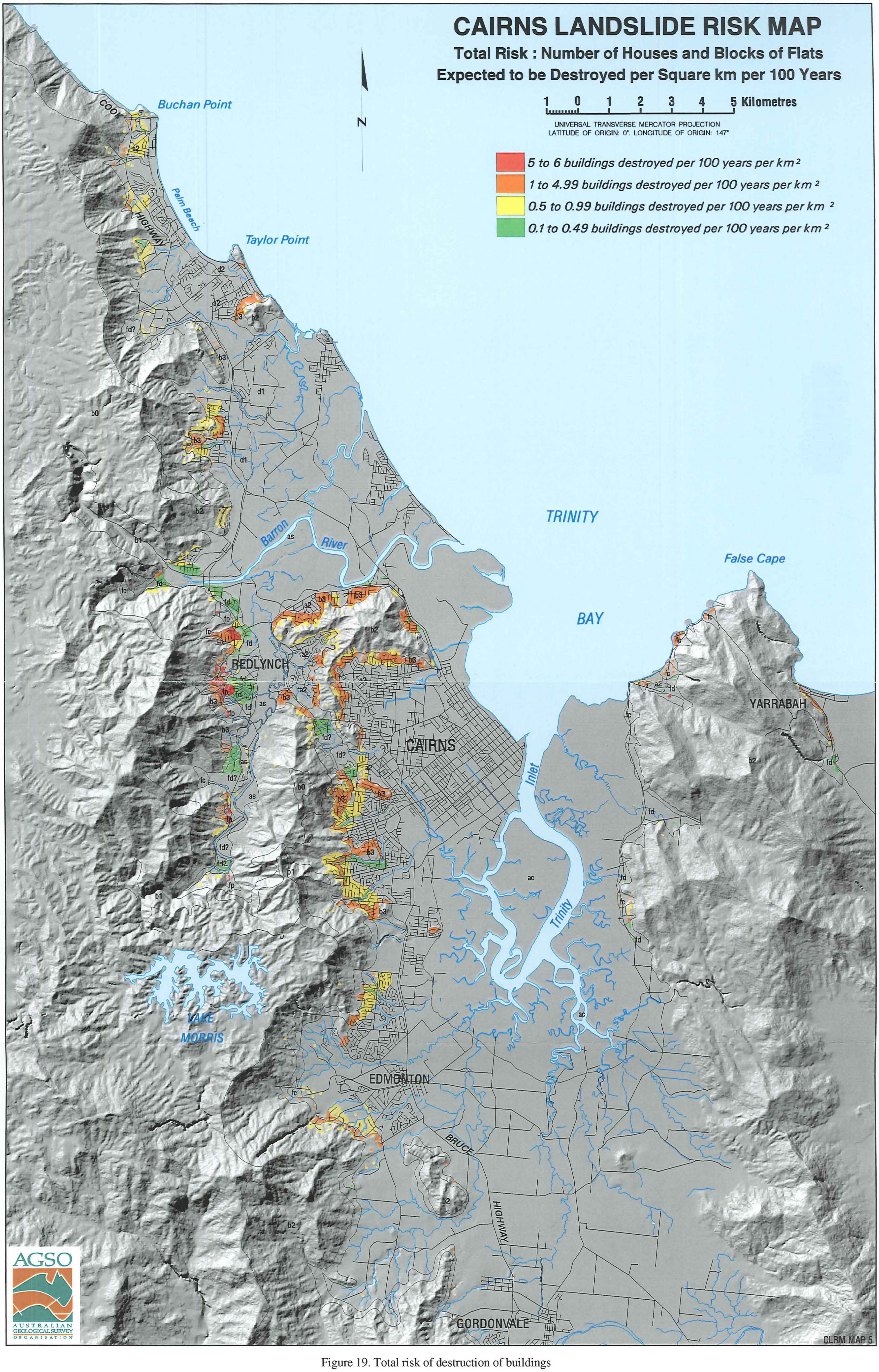

Figure 19. Total risk of destruction of buildings